Dounreay

PROJECT TITLE:

D3100 LLW Disposal Facilities

DOCUMENT TITLE:

Environmental Safety Case 2020

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ABSTRACT:

This Environmental Safety Case (ESC) presents the arguments and evidence for the protection of the public and the environment from disposal of solid low-level radioactive waste (LLW) in the D3100 LLW Disposal Facilities at Dounreay. This issue of the ESC builds on previous versions. ESC 2010 Issue 1 supported authorisation from the Scottish Environment Protection Agency (SEPA) under the Radioactive Substances Act 1993 to dispose of wastes in D3100. ESC 2010 Issue 2 was produced to account for changes made during design-and-build of the first phase of the disposal vaults and was issued just prior to the start of operations. ESC 2020 has been produced to support an application to SEPA to vary the D3100 Permit under the current legislation, the Environmental Authorisations (Scotland) Regulations 2018. This ESC takes account of a programme of work to review the limits and conditions in the D3100 Permit, and proposes a risk-based approach to managing waste disposals in D3100. Such an approach will continue to ensure that waste disposals are controlled such that the assumptions set out in the ESC are met, and will enable greater flexibility during waste acceptance to account for inventory uncertainty and to optimise disposal of LLW. None of the changes implemented in this ESC affect the central conclusions that the D3100 disposal facilities can be constructed, operated and closed safely and provide for long-term safety and containment.

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Document Revision History		
Issue Number	**Date**	**Summary**
Issue 1, Draft A	28/09/2020	First draft for review.
Issue 1, Draft B	19/02/2021	Revised in response to review comments from DSRL and Quintessa Ltd. Waiting on issued Optimisation, Facility Design, NoRaH, WA Rules and ESC Management Plan reports in order to finalise the ESC.
Issue 1, Draft C	7/05/2021	Revised in response to review comments from D. Galson and for consistency with issued versions of the following reports: Optimisation, Facility Design, NoRaH, WA Rules, ESC Management Plan and Register of Uncertainties.
Issue 1	28/05/2021	Approved for issue.

Summary of changes between ESC 2010 Issue 2 and ESC 2020.

Section	Revision
Section 1 and throughout	Reference updated to reflect replacement of RSA 93 with EASR 18, and replacement of the RSA 93 Authorisation with an EASR 18 Permit. Existing Facility now referred to as the LLW Pits Complex. The New LLW Facilities (NLLWF or Dounreay Facility D3100) are now referred to as the D3100 LLW Disposal Facilities (D3100 or LLWDF).

Section	Revision
Section 1	NDA plan to reclaim SLC ownership from the Cavendish Dounreay Partnership noted.
Section 2	Updated to refer to Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2017, Ionising Radiations Regulations 2017, and Technical Guidance WM3 (2018). Added publication of guidance on revocation (GRR). Updated the IAEA and NEA references. Added CAR authorisation details and noted PPC permit revocation.
Section 3	Updated the IAEA references. EC Directive recommendation on application of Article 37 added and noted implications for UK leaving EURATOM. Updated UK legislation references due to implementation of EC BSS update. Added reference to UK strategy for LLW from the nuclear industry. Added 2009 planning permission reference, and mention of boundary waste consideration in the inventory report. Added reference to 2009 UK strategy for radioactive discharges and its 2018 review, plus updated 2019 SEPA policy on optimisation and BPM. Added reference to Optimisation 2020 report.
Section 4	Updated to reflect the 2020 estimate of the D3100 LLW Inventory, sub-divided into sections on mass/volume, activity, materials, etc. and added sections on fissile inventory, uncertainties and inventory change from 2009. Updated to be consistent with WA Rules 2020 and changes in the overall waste acceptance processes for wastes consigned to D3100. Moved text on NoRaH and criticality safety assessment (CSA) to Section 7.
Section 5	Updated to reflect operational practice and optimisation studies since 2014. Added text on the change during operations to undertake a number of smaller, more regular, grouting campaigns in the LLW vaults, rather than undertaking two large interstitial grouting campaigns.
Section 6	Restructured description of the history of site characterisation into the three rounds of characterisation activities used in other ESC-supporting documentation. Revised the hydrogeology and geochemistry sections to report the latest data and note the differences between the baseline and present-day conditions. Updated discussion of potential future disruption using a variety of supporting references.
Section 7	Updated discussion and results of the D3100 PA to align with the Run 5 assessment, which uses the 2020 inventory estimate. Added discussion and results of an updated skyshine analysis, updated assessment of non-radiological hazards, and updated assessment of impacts on non-human biota. Consolidated criticality safety text into a new sub-section (7.11), with reference to CSA 2020.
Section 8	New section presenting proposed sum of fractions approach for controlling radionuclide content in D3100.
Section 9	(Previously Section 8.) General update to latest references.
Section 10	(Previously Section 9.) General update to refer to new monitoring baseline report, annual monitoring reports and evaluation.
Section 11	(Previously Section 10.) Added reference to DSRL's proposed position to the NDA for a 50 year institutional control period for D3100 and likely alignment with the control period for the Dounreay nuclear licensed site.
Section 12	(Previously Section 11.) Updated to reflect latest DSRL policy, document access on the NDA Hub, and general reference update.
Section 13	(Previously Section 12.) Minor update for consistency with rest of document and addition of a table summarising main changes for consideration in the Permit.
Section 14	(Previously Section 13.) Updated to reflect planned work and ongoing work as part of D3100 operations and management.
Appendix A	Updated to be consistent with WA Rules 2020.
Appendix B	Updated for consistency with rest of document.

SEPA has reviewed ESC 2010 Issue 1, but not ESC 2010 Issue 2. Therefore, to support traceability, the summary table of changes between ESC 2010 Issue 2 and ESC 2010 Issue 1 is repeated below.

Section	Revision
Section 1 and throughout	Reference updated to reflect issue of RSA 93 Authorisation in January 2013.
Section 1, 3 and 4	Revised waste definitions to be consistent with new RSA 93 exemption regulations.
Section 2	Removed Figure 2.3 showing old structure of ESC.
Section 3 – International	Revised for consistency with most recent IAEA publications.
Section 3 – UK	Updated references to Scottish policy (higher activity wastes) and regulatory framework.
Table 4.3	Updated to reflect Authorised inventory, which is based on waste activities as of 2009 AD.
Section 4 – Context	Updated to reflect 2011 ESC for the LLWR.
Section 4 – WAC	Updated WAC to be consistent with Waste Acceptance 2014.
Section 4 – WAC	Removed text on waste characterisation – the removed text concerned the waste consignor rather than the operator of the NLLWF.
Table 5.1 and Figure 5.8 and supporting text	Details of enhanced geosphere layer added.
Figures 5.2 to 5.4, Figure 5.6, Table 5.2	Updated / added to reflect revised layout and design.
Table 5.3	Updated to reflect most recent BPM / optimisation studies.
Section 6	Summary of ground investigations for Design and Build added.
Section 6	Details of SCP 2011 and Site Characteristics Summary 2014 added.
Figure 6.2 (replaces old Figures 6.2 and 6.3)	Now shows BM-series monitoring boreholes.
Figure 6.5	Added to show topographic profile after closure including the enhanced geosphere.
Section 6 – Land use and Section 7 – PEGs	Reference to 2008 SEPA habits survey added.
Figure 6.9, 6.10, 6.11 and 6.14 and text	Updated to reflect latest geological model.
Figure 6.12 and 6.13	Pictures of excavation added.
Section 6 – Hydrogeology and Table 6.2	Details of latest post-closure hydrogeological modelling added / updated.
Section 6 – Geochemistry and Tables 6.3 to 6.5	Baseline hydrochemistry and background radioactivity added.
Section 7	All text and figures updated to refer to the Run 4 PA.
Figure 7.4 and text	Model revisions for enhanced geosphere added.
Section 7 – Non-human biota	Text updated to reflect modelling using ERICA.
Section 8 – Design	Text updated to refer to Run 4 PA barrier performance analysis.
Table 8.1 and text	Updated to refer to Dounreay Authorisation, EC clearance levels, Scottish exemption levels and RIFE 17.
Section 8 – Confidence building	References to comparison with 2011 ESC for LLWR and peer review of Issue 1 of 2010 ESC added.

Section	Revision
Section 8 – Further confidence building	Reference to PA validation plan changed to discussion of Register of Uncertainties.
Section 9 – Table 9.1	Removed list of monitoring programmes, instead referring to environmental monitoring programme.
Section 9 – Table 9.2	Removed summary of ongoing monitoring, instead referring to annual report.
Section 10	Reference added to institutional control plan currently in development.
Section 11	Discussion of Operational Management Plan added.
Section 11 – Figure 11.1	New NLLWF DSRL management structure added.
Section 11 – Table 11.1	Deleted.
Section 11 – Figure 11.2	Deleted.
Section 11	References to non-technical summaries updated.
Section 13	Summary of forward programme activities updated.

EXECUTIVE SUMMARY

Background

E1 The Dounreay nuclear licensed site is being decommissioned, in accordance with UK Government policy. Work to date and future work at the site is expected to lead to the production of a significant volume (tens of thousands of cubic metres) of solid low-level radioactive waste (LLW), although waste generation will be minimised wherever practicable. A solution is required for the long-term management of the LLW.

E2 In 2002 the United Kingdom Atomic Energy Authority (UKAEA) made an application to the Scottish Environment Protection Agency (SEPA) to dispose of Dounreay LLW to the national Low Level Waste Repository (the LLWR) in Cumbria. In April 2004, UKAEA completed a study which concluded that the Best Practicable Environmental Option (BPEO) for managing Dounreay's LLW is disposal in shallow below-surface facilities to be constructed at Dounreay.

E3 On 10 May 2005, the Scottish Executive (now the Scottish Government) issued SEPA with a Direction to refuse the 2002 application to dispose of Dounreay LLW to the LLWR, and indicated instead that a new LLW disposal facility should be constructed on UKAEA-owned land at Dounreay.

E4 In April 2005, the Nuclear Decommissioning Authority (NDA) became responsible for managing the UK nuclear decommissioning programme. Under contract to the NDA, UKAEA continued the decommissioning programme at Dounreay.

E5 In 2008, Dounreay Site Restoration Limited (DSRL) took over the site licence and environmental authorisations and permits from UKAEA. As part of the decommissioning programme, DSRL pursued the development of new specialised facilities (the D3100 LLW Disposal Facilities) adjacent to the Dounreay nuclear licensed site for the disposal of solid LLW from the Dounreay nuclear licensed site and adjacent Ministry of Defence Vulcan site only. Planning permission from the Highland Council was received in early 2009 and construction of the first disposal vault commenced in 2012. In January 2013 SEPA issued an Authorisation under the Radioactive Substances Act 1993 (RSA 93) for disposal of radioactive wastes to D3100; waste disposal operations started in April 2015. RSA 93 was superseded by the Environmental Authorisations (Scotland) Regulations 2018 (EASR 18) in September 2018, and a new disposal Permit for D3100 was issued on 1 April 2019. In accordance with the Permit, the D3100 disposal facilities will not receive any intermediate-level waste, high-level waste or spent fuel. The D3100 facilities will also not receive non-radioactive wastes, such as exempt wastes and domestic wastes of the types that are typically sent to landfill.

Role of the ESC

E6 This document sets out the Environmental Safety Case (ESC) for D3100. The ESC is required to support the Permit from SEPA under EASR 18 for disposal of radioactive wastes with no intent to retrieve. The ESC demonstrates that the D3100 disposal facilities meet the Fundamental Protection Objective as specified in regulatory guidance on requirements for authorisation:

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

E7 The ESC will be progressively developed and enhanced as additional information is gathered through facility construction, operation and closure, until withdrawal of control over the facilities. In accordance with the environmental regulators' guidance, updated issues of the D3100 ESC are being provided to SEPA at key steps during the development of the facilities. The first versions of the ESC supported the application for planning permission for the construction of the facilities. ESC 2010 Issue 1 of ESC 2010 supported the RSA 93 Authorisation decision by SEPA, while Issue 2 of ESC 2010 (published in 2015) coincided with completion of construction of the first phase of disposal vaults and written agreement from SEPA to start waste emplacement.

E8 This iteration, ESC 2020, has been produced to support an application to SEPA from DSRL to vary the EASR 18 Permit to apply a risk-based approach to setting radioactivity limits for waste disposals in D3100. This approach is termed hereafter as a Sum of Fractions (SoF) approach. The SoF approach will ensure that waste disposals continue to be controlled such that the assumptions about the inventory set out in this ESC are met, and will enable greater flexibility during waste acceptance to account for inventory uncertainty and to optimise disposal of DSRL LLW. Underpinning assessments and waste acceptance procedures have also been reviewed and revised to support this ESC and reflect learning gained from operational experience over the last five years.

E9 Ongoing maintenance and management of the ESC is a condition of the EASR 18 Permit and there are some areas for further development of the ESC appropriate to the current status of D3100. A forward programme and an ESC Management Plan are presented for work in these areas and to build further confidence in the safety case.

Optimisation

E10 DSRL is developing two types of disposal vaults in phases, timed and sized to meet predicted waste arisings. One set of vaults will be used for disposal of LLW and a second set of vaults will be used for disposal of demolition wastes and soil with very low radioactivity content - a group of LLW streams termed Demolition LLW. The design of the facilities represents best practice for near-surface radioactive waste disposal facilities. The approach taken in the management of the wastes conforms to national and international policy and principles. Each decision in the development of D3100 has considered optimisation of radiological protection, taking into account issues such as economic and societal factors, to ensure that impacts from the facilities are As Low as Reasonably Achievable (ALARA). The location and general design of the facilities represent an optimised solution for the disposal of LLW on NDA-owned land at Dounreay. Optimisation studies will continue to be undertaken as further decisions are taken during construction, operation and closure of the facilities.

Environmental Safety Strategy

E11 In demonstrating compliance with the principles for radioactive waste management, the environmental safety strategy for the D3100 project requires that safety is paramount and central to the entire development process. In this context, the term "safety" can be regarded as representing the achievement of appropriate conditions during construction, operations and in the long-term after disposal, so as to provide an adequate and optimised level of protection to workers, members of the public and the environment from hazards. Key measures adopted by DSRL in implementing the environmental safety strategy include:

- Sound and open process (e.g. flexible, step-by-step development, extensive stakeholder dialogue, and peer review of key documents).
- Positive environmental safety culture supported by a management system that ensures effective leadership, proper arrangements for policy and decision making, a suitable range of competencies, provision of sufficient resources, a commitment to continuous learning and proper arrangements for succession planning and knowledge management.
- Use of robust and demonstrable safety measures (e.g. proven, well understood engineering technology, and long-term stability of the site).
- Strength in depth in the design through the use of multiple barriers and no sole reliance on single components or processes for regulatory compliance.
- Reliance on passive safety measures in the long-term (initially, although passive safety barriers are in place, safety is assured by active measures, such as monitoring and surveillance; in the longer term, after active measures are withdrawn, safety is inherent in the disposal system design, and is not reliant on human interventions).
- Structured, transparent and traceable demonstration of environmental safety during both the authorisation and post-authorisation periods, using internationally recognised assessment methods and tools.

Inventory

E12 The planning permission for the D3100 LLW disposal facilities specifies an upper limit of 175,000 m^3 of packaged waste. The EASR 18 Permit sets radioactivity limits for the total waste disposed of across all D3100 vaults for each key radionuclide. Limits in the extant Permit are based on the best estimate of the radioactive content of the waste as provided by DSRL in 2009. A revised inventory for 2020 is presented in this ESC, as well as a proposal to use a risk-based SoF approach during waste acceptance to be more flexible in defining the permitted radioactivity levels in each waste consignment. The SoF approach uses a calculation relating the design and performance of the facility, individual radionuclide properties and the regulatory performance measures.

E13 The levels in the SoF approach are set to ensure that the facilities comply with the regulatory environmental protection objectives. The waste to be emplaced in D3100 contains less than 0.01% of the radioactivity that is present in radioactive waste on the Dounreay site, but comprises about 90% of the radioactive waste by volume that is expected to be created during operation and decommissioning of the site. The radioactive waste has only a very low content of non-radiological hazardous materials associated with it.

E14 The majority of the activity in the LLW derives from short-lived radionuclides (i.e. half-lives shorter than ~30 years). The facilities have been designed such that no routine releases of radioactivity are expected before the facilities are closed. During the initial 300-year period after closure, while the majority of the radioactivity decays, the containment system will severely limit the migration of radionuclides. In 300 years, roughly 90% of the total radioactivity initially disposed of will have decayed naturally and the hazard from the waste will therefore be significantly reduced.

Multiple Barriers and their Safety Functions

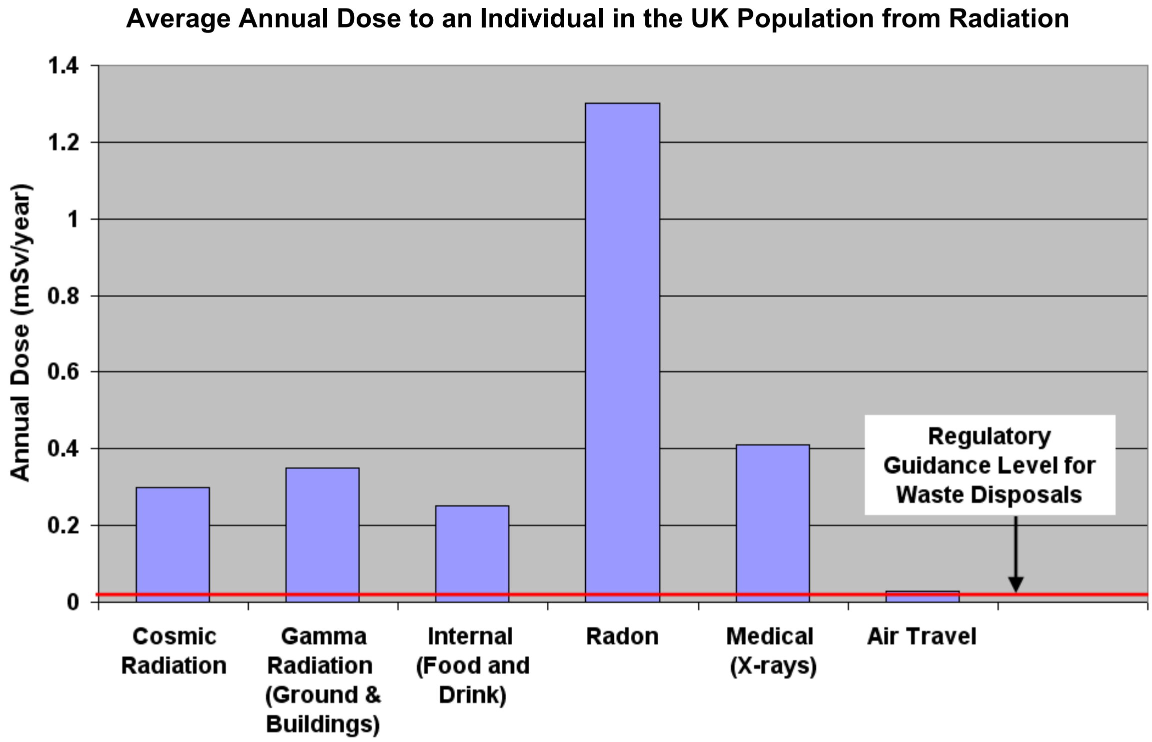
E15 For the long-term, the facilities have been located and designed to protect against releases to groundwater and the wider environment, disruption by inadvertent human actions, and disruption by coastal erosion. The use of multiple engineered barriers provides assurance that even if one barrier exhibits poor performance, the other barriers will ensure that the required overall performance is achieved. The engineered barriers include the concrete box structure of the facilities and the engineered cap, which inhibit migration of groundwater into and out of the facilities. Within the LLW vaults, the waste will be encapsulated in grout that acts both to reduce groundwater movement within the vaults and as a chemical inhibitor to radionuclide migration. Demolition LLW presents a very low hazard and, as such, has been assessed as not requiring conditioning or backfilling with a cementitious grout; the thick concrete walls of the Demolition LLW vaults are sufficient to ensure adequate containment of the hazard.

E16 Collectively, the engineered barriers will ensure that releases of radioactivity will remain low for tens of thousands of years under undisturbed conditions. Locating the wastes below the surface and over 200 m inland from the coast significantly reduces the risk of disruption of the facilities by inadvertent human actions and coastal erosion during this period. The cap will also be designed to deter potentially disruptive human activities. Provided the facilities are not disrupted, radionuclide releases from the facilities will be to groundwater. A further engineered barrier, termed the “enhanced geosphere”, consists of a layer of excavated material over the land surface between the facilities and the coast. This layer will limit radioactivity released to groundwater reaching the ground surface and ensure that it migrates through the rock to sea. Even with pessimistic assumptions on barrier performance, the maximum annual flow or release of radioactivity from the facilities to groundwater and then to the sea would still only be comparable to the flow of naturally occurring radioactivity that is currently migrating through the rock at Dounreay.

Calculated Impacts

E17 The calculated peak annual releases of activity from the D3100 disposal facilities into the environment and, more specifically, into the sea, are less than the permitted levels of annual liquid discharges from the Dounreay site into the sea. Even if the total cumulative releases of alpha and beta/gamma activity from the facilities over 100,000 years are considered, the total activity release is only similar to previous authorised discharges from the Dounreay site for one year.

E18 Quantitative safety assessment calculations have been undertaken by DSRL to evaluate the potential radiological impacts of D3100. The safety assessment calculations have been developed using an internationally accepted methodology and have been peer reviewed. In the reference case considering the best estimate of the likely final D3100 inventory, the calculated peak annual radiological dose rates to a representative of the most exposed group are low - considerably less than 0.01 millisievert per year (mSv y^{-1}). Therefore, the safety assessment results indicate that the D3100 disposal facilities meet the regulatory safety criteria and guidance for radiological protection of the public. By complying with the regulatory guidance, the maximum radiological dose that might be received by any individual through releases from D3100 will be less than one hundredth of the average radiological dose received by an individual in the UK population from naturally occurring radiation; that is, D3100 does not noticeably affect the total annual radiological dose received by any individual (see the chart below). If the facilities are disrupted by coastal erosion thousands of years in the future, radiological doses to the public on the coastline will still be less than the regulatory guidance level. Similarly, if the facilities are disrupted inadvertently at any time by human activities in the post-authorisation period, radiological doses to the disrupting individuals and to any users of the disrupted area afterwards will be below the regulatory lower dose guidance level of 3 mSv y^{-1} for such events.



E19 For non-human biota, considered across the marine and terrestrial environments, calculated peak doses to all organism types generally comply with internationally agreed standards. Calculated concentrations of radioactivity in the environment (in rocks, soils, air, water and vegetation) related to releases from D3100 are similar to, if not significantly below, local concentrations of naturally occurring radioactivity.

E20 Regarding non-radiological impacts, the high standard of engineering in D3100 provides long-term protection of humans and the environment against the small amount of non-radiological hazards in the wastes.

Treatment of Uncertainties

E21 To take account of uncertainties, the safety assessment is based on cautious modelling assumptions to illustrate the potentially most significant consequences of a given pathway or combination of pathways. In particular, cautious assumptions have been adopted regarding releases of radioactivity into infiltrating groundwater (rapid failure of packaging, instantaneous dissolution of radionuclides), migration of radioactive gases (instant release), and behaviour of potentially exposed humans (deriving key foodstuffs from the small area of land potentially contaminated by releases from the facilities). In reality, humans engaged in the far future in activities similar to those that are currently observed along the coast near Dounreay are likely to receive extremely low doses compared to the hypothetical humans modelled in this ESC, which already shows compliance with the regulatory guidance.

Operations and Waste Acceptance

E22 An Operational Management Plan (OMP) has been prepared for the D3100 LLW disposal facilities that details how the facilities are to be operated, including procedures for ensuring protection of workers, the public and the environment, monitoring, and waste acceptance. Authorised Waste Acceptance Criteria (WAC) in the EASR 18 Permit set out what DSRL is required to comply with for D3100 in terms of waste acceptance. The Authorised WAC include limits on total waste activities.

E23 DSRL has developed a waste acceptance process for D3100 to ensure that wastes consigned to the facilities are consistent with the ESC, regulatory requirements and guidance, and DSRL operational requirements. Key to the process is a set of Waste Acceptance (WA) Rules that map waste properties to assumptions in the ESC and underlying reports; the Authorised WAC are incorporated into the broader set of WA Rules.

E24 The Dounreay site has a separate EASR 18 Permit that permits transfer of waste from the site to D3100 for disposal. DSRL has established a separate D3100 Compliance team, independent from site waste consignors, to manage the facilities. Acceptance of wastes into D3100 is conditional on site waste consignors demonstrating that the wastes are compliant with the D3100 WA Rules. This condition is implemented on the Dounreay site through the DSRL Waste Management Process. The DSRL Waste Management Process and the overarching DSRL management system and safety culture have been deemed appropriate by SEPA initially through the issuing of the Authorisation/Permit and, subsequently, through written agreement for the start of waste emplacement.

Summary: Confidence in Environmental Safety

E25 Safety features that provide confidence in the environmental safety of D3100 include:

- Good design, for example
  - using an isolate-and-contain strategy;
  - multiple engineered barriers;
  - reliance on passive long-term safety; and
  - choosing a suitable stable site and adapting to the site characteristics, as required.
- Low hazardous nature of the LLW, for example
  - limiting the near-field source term through waste acceptance requirements.
- Quality of implementation, for example
  - working within a well-defined legal and regulatory framework;
  - using the well-established DSRL management system, further developed to provide an appropriate degree of separation between the Dounreay site consigning waste to D3100 under its EASR 18 Permit and D3100 accepting waste under its own EASR 18 Permit;

- demonstrating optimisation;
- applying the waste acceptance process and an emplacement strategy;
- adequate resourcing; and
- assuring construction quality and using commissioning tests, where practicable.

* Safety assurance, for example
  - demonstrating operational and post-closure environmental safety;
  - monitoring performance, as necessary;
  - optimising closure;
  - using independent scrutiny and peer reviews of key project documentation and of construction quality; and
  - protecting the site using both active controls (e.g. site monitoring) and passive controls (e.g. anti-intrusion layer in the cap).

E26 None of the changes made between the previous ESC (ESC 2010 Issue 1 and Issue 2) and this issue (ESC 2020 Issue 1) regarding, for example, design, layout, construction and operation, affect the central conclusions that the D3100 LLW Disposal Facilities can be constructed and operated safely and provide long-term safety and containment.

E27 Section 13 of this ESC presents a table that summarises the main changes for consideration by SEPA in the evaluation of the application to vary the D3100 Permit.

CONTENTS

LIST OF ACRONYMS

ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
AOD	Above Ordnance Datum
BEIS	Department for Business, Energy and Industrial Strategy
BGS	British Geological Survey
BNFL	British Nuclear Fuels Limited
BM	Baseline Monitoring
BP	Before Present
BPEO	Best Practicable Environmental Option
BPM	Best Practicable Means
BSS	Basic Safety Standards
CAR	Water Environment (Controlled Activities) Regulations
CCB	Crofting Community Body
CfA	Conditions for Acceptance of waste
CQA	Construction Quality Assurance
CSH	Calcium-Silicate-Hydrate
CWCC	Caithness West Community Council
DCGL	Derived Concentration Guideline Levels
DECC	Department of Energy and Climate Change (this became part of the Department for Business, Energy and Industrial Strategy, BEIS, in July 2016)
Defra	Department for Environment, Food and Rural Affairs
DMS	Dounreay Data Management System
DRWI	Dounreay Radioactive Waste Inventory
DSRL	Dounreay Site Restoration Limited
EASR 18	Environmental Authorisations (Scotland) Regulations 2018
EC	European Commission
EIA	Environmental Impact Assessment
EMP	Environmental Monitoring Programme
EMProg	Dounreay Site Environmental Monitoring Programme
EQ	Enviros QuantiSci
ERICA	Environmental Risk from Ionising Contaminants: Assessment and management

ESC	Environmental Safety Case
FEP	Feature, Event and Process
FSA	Food Standards Agency
GDL	Generalised Derived Limit
GI / GIR	Ground Investigation or Ground Investigation Report
GIS	Geographic Information System
GRA	Near-Surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation, February 2009
GSL	Galson Sciences Limited
HAW	Higher Activity Waste
HAZOP	HAZard and OPerability
HHISO	Half Height International Standards Organisation freight container
HLW	High-Level radioactive Waste
HPA	Health Protection Agency – Radiation Protection Division (formerly National Radiological Protection Board – NRPB), succeeded by Public Health England (PHE) as of 1 April 2013, and currently (August 2020) being replaced by the National Institute for Public Health (NIPH)
HSE	Health and Safety Executive
HVLA	High Volume Low Activity waste (also LAHV or VLRM - Very Low Radioactive Material)
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ILW	Intermediate-Level radioactive Waste
IMAGES	Information Management and Geographical Evaluation System
IPCC	Intergovernmental Panel on Climate Change
ISAM	Improvement of Safety Assessment Methodologies for near-surface waste disposal facilities (IAEA)
ISO	International Standards Organisation
LLW	Low-Level radioactive Waste
LLWDF	LLW Disposal Facilities (also referred to as D3100)
LLWR	Low-Level Waste Repository, Cumbria
LMP	Load Management Plan
MoD	Ministry of Defence
MP	Member of Parliament
MSP	Member of the Scottish Parliament
NDA	Nuclear Decommissioning Authority

NEA	Nuclear Energy Agency
NIPH	National Institute for Public Health (successor to HPA and PHE)
NLLWF	New Low Level Waste Facilities (now referred to as D3100 or the LLW Disposal Facilities)
NoRaH	Non-Radiological Hazard
NRTE	(Vulcan) Naval Reactor Test Establishment
OECD	Organisation for Economic Co-operation and Development
OMP	Operational Management Plan
ONR	Office for Nuclear Regulation (replacing the Nuclear Installations Inspectorate [NII])
OoSoR	Out of Scope of Regulation
PA	Performance Assessment
PBO	Parent Body Organisation
PCRSA	Post-Closure Radiological Risk Assessment
PCSC	Post-Closure Safety Case
PEG	Potentially Exposed Group (terminology now replaced by Representative Person)
PHE	Public Health England (successor to HPA, but currently (August 2020) being succeeded by National Institute for Public Health (NIPH))
PMP	Project Management Plan
PPC	Pollution Prevention and Control
PRC	Proportionate Regulatory Control
PSWP	Project Specific Waste Plan
PWI	Predictive Waste Inventory
REPPIR 19	Radiation Emergency Preparedness and Public Information Regulations 2019
RIFE	Radioactivity In Food and the Environment
RP	Representative Person
RSA 93	Radioactive Substances Act 1993
RWMC	Radioactive Waste Management Committee (NEA)
SCP	Site Characterisation Plan
SEPA	Scottish Environment Protection Agency
SHE	Safety, Health and Environmental
SLC	Site Licence Company
SoF	Sum of Fractions

STP	Standard Temperature and Pressure
SWB	Site Water Balance
SWESC	Site Wide ESC
TLD	Thermoluminescent Dosimeter
UKAEA	United Kingdom Atomic Energy Authority
UKRWI	UK Radioactive Waste Inventory
VLLW	Very Low-Level radioactive Waste (also High Volume or HV VLLW)
WA	Waste Acceptance
WAC	Waste Acceptance Criteria
WA Rules	Waste Acceptance Rules
WASSC	WAste Safety Standards Committee (IAEA)
WCTP	Waste Compliance Test Plan
WRACS	Waste Receipt Assay Characterisation and Supercompaction facility

1 INTRODUCTION

1.1 Background

1 Dounreay Site Restoration Limited (DSRL) is carrying out an environmental site decommissioning and restoration programme at the Dounreay nuclear licensed site in Caithness in the north of Scotland ([1]; Figure 1.1). Dounreay was the UK's former centre for fast breeder reactor research and development. The decommissioning and restoration programme is being undertaken over a number of decades, during which a significant volume of treated and packaged solid low-level radioactive waste will be produced [2, p.141]. This waste is being managed, and must continue to be managed, in line with UK National and Scottish radioactive waste policy [3] and in accordance with safety and environmental regulations.

2 Throughout this document, solid radioactive low-level waste is considered in two groups:

- *Low-level radioactive waste (LLW).* The UK national category of normal operational and decommissioning LLW, as defined in UK radioactive waste management policy [3]. This is radioactive, operational and decommissioning waste within the UK LLW category limit (not exceeding 4 GBq te^{-1} of alpha or 12 GBq te^{-1} of beta/gamma activity), but excluding the group of Demolition LLW streams described below. It presents a low risk and is easily managed through controlled and contained manual and automated processes.
- *Demolition LLW[1].* A DSRL-defined group of LLW streams comprising unconditioned material including, but not restricted to, concrete, bricks, metals, stone, sand and soil, with low radiological and non-radiological hazards. The radioactive content of Demolition LLW does not exceed 0.01 GBq te^{-1} of alpha or 0.40 GBq te^{-1} of beta/gamma activity. Demolition LLW presents a very low risk and can be safely managed using less engineering than higher activity LLW.

3 In the past, the Dounreay site disposed of its operational LLW and some hazardous waste at its own authorised LLW disposal facility on-site – hereafter referred to as the LLW Pits Complex (Figure 1.1). Disposals to the LLW Pits Complex, consisting of seven shallow excavations cut into the bedrock, began in 1959 and continued routinely over the next four decades, disposing of a total waste volume of around 33,000 m^3 [4]. The facility is now full and is temporarily capped with low-permeability cover. During the early 1990s, the operator of the Dounreay site was the United Kingdom Atomic Energy Authority (UKAEA), and UKAEA obtained planning

1 In other studies at Dounreay, Demolition LLW has been variously referred to as High Volume Low Activity waste (HVLA), LAHV, or VLRM (Very Low Radioactive Material). These terms have now been replaced by Demolition LLW, but these alternative acronyms remain in some supporting references. Note that Demolition LLW has significantly higher activity limits than the High Volume Very Low Level Radioactive Waste (HV VLLW) sub-category of LLW defined by UK policy [3].

permission from the Highland Council for a small extension to the LLW Pits Complex, but decided not to implement this development as it would not provide a long-term solution for all of the projected waste arisings. UKAEA considered that further work on long-term strategy and environmental issues was required.

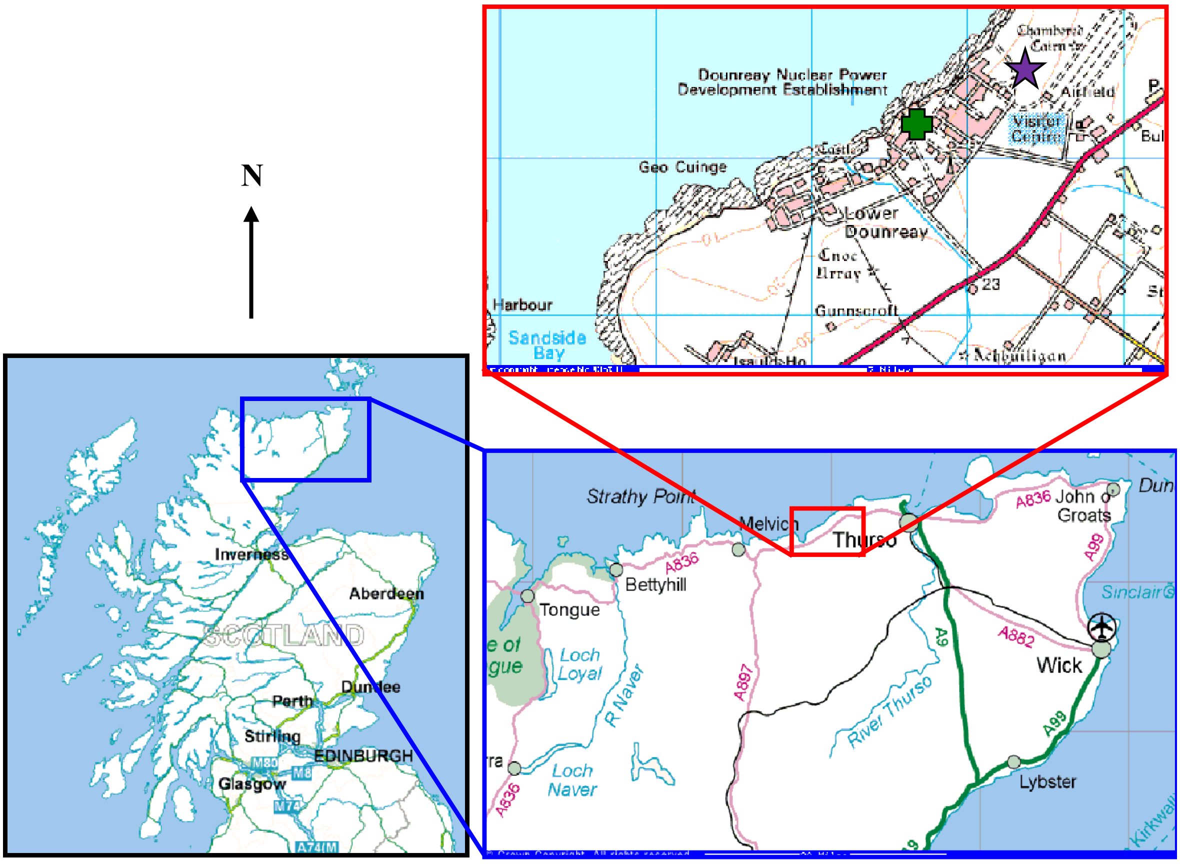


Figure 1.1: Location of the Dounreay nuclear licensed site in Northern Scotland. Green cross in top right box shows the position of the LLW Pits Complex and the purple star shows the location of the D3100 LLW Disposal Facilities.

4 The development of the overall management strategy for LLW at Dounreay was progressed in four principal areas [5]:

- *Waste minimisation.* Policy at Dounreay is to reduce the overall volume of waste produced, minimise the volume of waste that must be managed as radioactive waste, and ensure that radioactive waste is appropriately managed within the lowest radiological category possible.
- *Disposal of Dounreay LLW at the existing UK LLW Repository in Cumbria (the LLWR).* An application for disposal of current arisings of Dounreay's LLW to the LLWR was made to the Scottish Environment Protection Agency (SEPA) in May 2002 [5, ¶17]. The intention was that this route would deal with arisings of Dounreay LLW that conformed to the LLWR's conditions for acceptance until a long-term strategy was developed and in place for Dounreay LLW. However, in May 2005, the Scottish Government issued a Direction to SEPA to refuse UKAEA's 2002 application to transfer LLW from

Dounreay to the LLWR for disposal [6]. The accompanying Explanatory Note to the Direction by Scottish Ministers endorsed UKAEA's long-term strategy for disposal of Dounreay's LLW at Dounreay [6, ¶5].

- *Interim arrangements for LLW and Demolition LLW management.* An interim storage capacity for LLW and Demolition LLW arisings at Dounreay was developed. As well as providing an ongoing capability for short-term management of waste arisings, the storage capacity also provided a stop-gap for waste handling while the long-term strategy for management of the wastes was developed and implemented.

- *Further development and initial implementation of the long-term strategy for LLW and Demolition LLW management following on from the above steps.* This has been done in three overlapping stages (1999-2005; 2005-2010; 2008-2015), as summarised in the following paragraphs (see also Figure 2.1), followed by waste disposal operations (2015- onwards).

5 **Stage 1** (1999-2005) of the Dounreay LLW long-term management strategy development project involved a Best Practicable Environmental Option (BPEO) study [7] to provide an objective review of LLW management options. The use of a BPEO analysis to support the decision-making process is consistent with UK best practice [8]. The BPEO study was supported by around sixty individual technical assessments and reports (see Appendix 7 of [7] for a complete list of Stage 1 technical reports). Three stakeholder workshops were held to review the options and identify the features and issues that were considered important by stakeholders. These workshops were followed by a three-month public consultation exercise.

6 The BPEO identified in Stage 1 for the long-term management of Dounreay LLW was to construct new LLW disposal facilities on UKAEA-owned land at Dounreay. Following discussion with stakeholders, including the Scottish Government and regulators, the BPEO was adopted in 2005 as the long-term strategy [5]. The disposal facilities, hereafter referred to as the D3100 LLW Disposal Facilities[2] (D3100 or LLWDF), are to accept LLW and Demolition LLW from the Dounreay nuclear licensed site and adjacent Ministry of Defence (MoD) Vulcan Naval Reactor Test Establishment (NRTE) site only. The D3100 disposal facilities will not receive any intermediate-level waste (ILW), high-level waste (HLW) or spent fuel. The facilities will also not receive non-radioactive wastes, such as putrescible domestic wastes, that are usually sent to landfill. Also consistent with the BPEO findings, the strategy considers retrieval of the wastes disposed of in the LLW Pits Complex, assay and re-packaging of the wastes, and disposal in D3100.

7 **Stage 2** of the D3100 project commenced in April 2005 and involved the development of the scheme design for the facilities, application for planning permission, and production of the documents required for regulatory authorisation of the facilities. Planning consent was obtained in early 2009 and the regulatory permit application was then submitted to SEPA in 2011.

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[2] In the original application documents the D3100 LLW Disposal Facilities were referred to as the New LLW Facilities (NLLWF or Dounreay Facility D3100).

8 From 1 April 2005, the Nuclear Decommissioning Authority (NDA) became responsible for managing the UK nuclear decommissioning programme. This meant that the NDA assumed ownership of Dounreay. UKAEA was contracted by the NDA to carry out an agreed programme of work at Dounreay, including progression of the LLW management strategy. On 1 April 2008, DSRL became the new Site Licence Company (SLC) at Dounreay, taking over the site licence and environmental permits and assuming responsibility for the decommissioning programme at Dounreay on behalf of the NDA. DSRL is a wholly-owned subsidiary of the Cavendish Dounreay Partnership, a consortium of Cavendish Nuclear, Jacobs and Amentum, who took over the DSRL parent body organisation (PBO) contract in April 2012 from UKAEA[3]. On 10 July 2020 the NDA announced that DSRL will become a wholly-owned subsidiary of the NDA in March 2021 [9]. Prior to the ownership transfer DSRL will remain under the management and direction of the Cavendish Dounreay Partnership.

9 National developments could affect the current long-term strategy. Therefore, a staged decision-making process and programme was adopted for implementing and adjusting the Dounreay LLW management strategy. The staged process and programme were supported by the NDA [10] and the regulators [11]. Points in the programme were identified for the NDA to review both national and Dounreay strategy and, with advice from regulators and the Scottish Government, approve the forward actions and funding for the D3100 project. This created sufficient flexibility for the NDA to allow DSRL to progress with the implementation of the long-term strategy[4].

10 **Stage 3** (2009-2015) of the D3100 project included regulatory approval and the Detailed Design and Build of the Phase 1 vaults, which consists of construction of two vaults, one each for LLW and Demolition LLW, and includes the necessary roads, infrastructure and services. Detailed design commenced in 2011 and construction of the first disposal vault started in 2012, with construction completed in May 2014. The vaults are located immediately to the northeast of the Dounreay licensed site, on NDA-owned land. Construction of the D2179 grout encapsulation plant for waste conditioning on the main Dounreay site was completed in September 2014. Inactive and active commissioning of both D3100 and D2179 was then undertaken, before the first waste was emplaced at D3100 in April 2015.

11 D3100 was authorised for the disposal of LLW and Demolition LLW under the Radioactive Substances Act 1993 (RSA 93) by SEPA in January 2013 [12] and varied by SEPA in 2015 [13]. RSA 93 was superseded by the Environmental Authorisations (Scotland) Regulations 2018 (EASR 18) on 1 September 2018, and a new disposal permit (EAS/P/1173599 [14]) issued on 1 April 2019. The RSA 93

3 At the time of contract award the consortium was called the Babcock Dounreay Partnership and comprised Cavendish Nuclear (then referred to as Babcock International before rebranding), CH2M Hill and URS. Jacobs purchased CH2M Hill in 2017. URS subsequently merged with AECOM. The part of AECOM involved in the PBO contract was then sold in February 2020 and the new corporate entity called Amentum.

4 Throughout this document, commitments made by DSRL are made on behalf of the NDA, which will oversee and finance all future developments.

Authorisation was deemed a permit under EASR 18, such that the new Permit was enacted by means of a variation (EAS/P/1173599 VN01 [15]).

12 Subsequent phases of vault construction and operation will be timed and sized to meet future waste arisings. The planning application [16] foresaw three phases of vault construction and operation, leading to the creation of six vaults with a total capacity of 175,000 m^3:

- Phase 1 Vaults - LLW Vault 1 and Demolition LLW Vault 1.
- Phase 2 Vaults - LLW Vault 2 and Demolition LLW Vault 2.
- Phase 3 Vaults – LLW Vault 3a and LLW Vault 3b to cater for LLW retrieved from the historical LLW Pits Complex, if this occurs.

13 The timings of the D3100 project have been derived and are reviewed as necessary to support the closure programme for the Dounreay site, with the aim of completing decommissioning and remediation activities to reach the currently-programmed Interim End State in 2032 [2, p.141]. The UK government's proposed amendments to the legislative framework for nuclear sites means operators will have greater flexibility to optimise site end states [17]. As such, site end states are under review for all NDA sites. The end state for the Dounreay site is complex, so DSRL is considering individual components of the site that together contribute to the site end state. These components include installations, current and future disposals, areas of land contamination, sub-surface structures and other discrete site conditions [2, p.40]. DSRL has reached the stage of updating the credible options for the Dounreay site end state assumption, with the aim to identify an underpinned and optimised site end state assumption over the next two years. Decisions yet to be taken will influence the volumes and timings of decommissioning wastes requiring disposal in D3100, as discussed in Sections 3.3 and 4.3. Any decisions taken will also be subject to an ongoing programme of optimisation and will not be final until the point of implementation. Therefore, the order and specification of future phases of D3100 vault construction may change from that originally envisaged in order to meet changes in projected waste arisings [18]. Figure 1.2 shows the location of the D3100 disposal facilities adjacent to the main nuclear licensed site and Figure 1.3 provides a closer view of the two vaults constructed so far: the D3120 LLW Vault 1 and the D3130 Demolition LLW Vault 1. Vaults to be constructed in future phases will be located between the current vaults and the foreground in Figure 1.2 (i.e. at the bottom of the photograph).

Figure 1.2: Aerial view of the Dounreay site with the D3100 disposal facilities in the foreground (c.2015). South to north is left to right.

Figure 1.3: Aerial view of the D3100 LLW disposal facilities during construction (2012-2014). The D3130 Demolition LLW vault is on the left of the photograph and the D3120 LLW vault is on the right.

1.2 Purpose of the Environmental Safety Case

14 A variety of documents is needed for submission to the regulatory and planning authorities to gain approval for the construction and operation of D3100 for disposal of LLW and Demolition LLW at Dounreay. One such document is this Environmental Safety Case (ESC). The main function of the ESC is to inform and support an authorisation from SEPA for the facilities to dispose of radioactive waste under environmental protection legislation, namely EASR 18. Maintenance of an ESC is required under Condition 6 of the D3100 Permit [14].

15 There are no specific requirements in EASR 18 about the safety case that must be made for a radioactive waste disposal facility. To address the need for guidance on the requirements for authorisation[5], including those requirements for a safety case, the UK environment agencies have published a document entitled "Near-surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on the Requirements for Authorisation", commonly termed the GRA [19]. The GRA was originally published in 1996 [20], and early issues of the D3100 ESC were developed to address the 1996 requirements. However, the GRA was revised in 2009 [19] and updated the regulatory requirements with regard to developments in radioactive waste disposal practice and regulation[6]. The 2009 GRA defines an ESC as [19, Glossary]:

> *"The collection of arguments, provided by the developer or operator of a disposal facility, that seeks to demonstrate that the required standard of environmental safety is achieved."*

16 This definition is consistent with international guidance on the preparation and content of a safety case[7] for radioactive waste disposal facilities, including guidance from the Nuclear Energy Agency (NEA, [21; 22]) and the International Atomic Energy Agency (IAEA, [23; 24; 25]). The safety case has three main, interrelated objectives:

- addressing regulatory requirements;
- providing broader arguments for safety; and
- building confidence in safety.

17 The national and international guidance notes that a safety case will develop and become more comprehensive as a programme progresses, and the developing safety case is a key input to decision making at several steps in the planning and implementation process, supporting optimisation of facility design and operation (e.g.

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5 At the time of the original application, the D3100 site had an 'Authorisation' under RSA 93 that has now been replaced by a 'Permit' under EASR 18. In this report, however, the term authorisation has been retained where appropriate, consistent with the terminology in the extant version of the GRA [19] and with Condition 1.1, Schedule 1, of the Permit [14].

6 The environment agencies are currently reviewing and updating the GRA once more, with an intent to published revised guidance in 2021/22.

7 Outside the UK, the more generic term "safety case" is generally used in the context of radiological protection, rather than the more specific term "environmental safety case" in the context of UK environmental protection legislation.

[19; 21; 23]). The D3100 ESC has been developed throughout the D3100 project, with major iterations produced to support key stages in the process:

- The first iteration of the D3100 ESC was submitted to SEPA in 2006 to inform initial regulatory dialogue and programme development [26].
- ESC 2008 [27] was produced to support a planning application to the Highland Council.
- ESC 2010 Issue 1 [28] was evaluated by SEPA and led to the authorisation of D3100 in 2013.
- ESC 2010 Issue 2 [29], produced in 2015, reflected the as-built vaults and coincided with written agreement from SEPA under the Authorisation for waste disposals to commence.

18 This iteration of the D3100 ESC and supporting references has been produced to support an application to SEPA to vary the Permit to apply a risk-based approach to setting radioactivity limits for waste disposals in D3100 through application of a Sum of Fractions (SoF) approach (this is discussed in detail in Section 8). Such an approach will continue to ensure that waste disposals are controlled such that the assumptions about the inventory set out in the ESC are met, and will enable greater flexibility during waste acceptance to account for inventory uncertainty and to optimise disposal of DSRL LLW.

19 As part of the Permit variation application, DSRL has also taken the opportunity to propose revisions and/or simplifications to waste acceptance criteria regarding management of non-radiologically hazardous (NoRaH) materials, and fissile material controls. The proposed revisions, which are discussed in Sections 4.4, 7.10 and 7.11, reflect changes as a result of learning from operational experience, and changes resulting from updates to legislation and guidance.

20 The ESC will continue to be developed to account for dialogue with SEPA and the development of the D3100 project throughout the ongoing forward programme. The ESC is needed to both inform and support regulatory decisions [19, ¶7.2.12]. The scope and structure of the ESC, and the iterative development of the ESC during the authorisation, construction, operation and eventual closure of the facilities, is discussed in more detail in Section 2.

21 Organisations have changed over the lifetime of the D3100 ESC. The organisation name at the time the relevant work was undertaken is cited in the main text, but any changes since are set out in a footnote and are acknowledged in the list of acronyms.

2 SCOPE AND STRUCTURE OF THE SAFETY CASE

2.1 Scope of the Environmental Safety Case

22 The development of D3100 is subject to a number of regulations administered through a variety of authorities. There are three principal sets of regulations:

- Planning regulations. A planning application for D3100 was submitted to the Highland Council in 2008 and included an Environmental Statement [16]. In accordance with the Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 1999[8], the Environmental Statement was informed by an Environmental Impact Assessment (EIA) which concentrated on the non-radiological environmental impacts of the development, such as those associated with construction noise, traffic, and material use, and their mitigation, but that also considered potential radiological impacts at a high level, informed by the first iteration of the ESC.
- Health and safety regulations. D3100 will not require a nuclear site licence from the Office for Nuclear Regulation (ONR)[9] as the disposal facilities are out with of the scope of the Nuclear Installations Act 1965. However, DSRL has developed health and safety documentation for D3100 in the same manner as the documentation for the ONR-licensed facilities at Dounreay on the basis that it represents best practice for ensuring that health and safety requirements (e.g. those under the Ionising Radiations Regulations 2017) are met. The documentation includes consideration of radiological doses to workers during operations, and risks to workers and the public associated with accidental releases during operations (e.g. [30]). Note that worker doses and accident risks are not covered under EASR 18 and are not covered in this ESC.
- Environmental protection and waste disposal regulations. There are several pieces of environmental protection legislation governing the construction, operation and closure of D3100. In particular, authorisation from SEPA under EASR 18 is required for all disposals of solid radioactive waste to a disposal facility. The permit granted by SEPA under EASR 18 considers safety to the public and the environment from routine exposures and discharges of radioactivity during operations and the potential impact of releases after closure. As stated in Section 1, the primary function of this version of the ESC is to support continued authorisation by SEPA of disposals under EASR 18.

23 Maintenance of the ESC is required by the EASR 18 Permit [14]. The development of the ESC and other project documentation is illustrated in Figure 2.1. Iterations of the ESC to-date, both before and since receipt of the EASR 18 Permit, have been

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8 The legislation currently in force is the Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations 2017.

9 Nuclear site licences are issued by ONR under the Nuclear Installations Act 1965. ONR was established as the licensing authority by The Energy Act 2013.

linked with completion of phases of site characterisation, design and construction, and safety assessment. Regulatory comments have been addressed on an ongoing basis, and the ESC has been used to help identify where and how gaps need to be filled through a forward work programme.

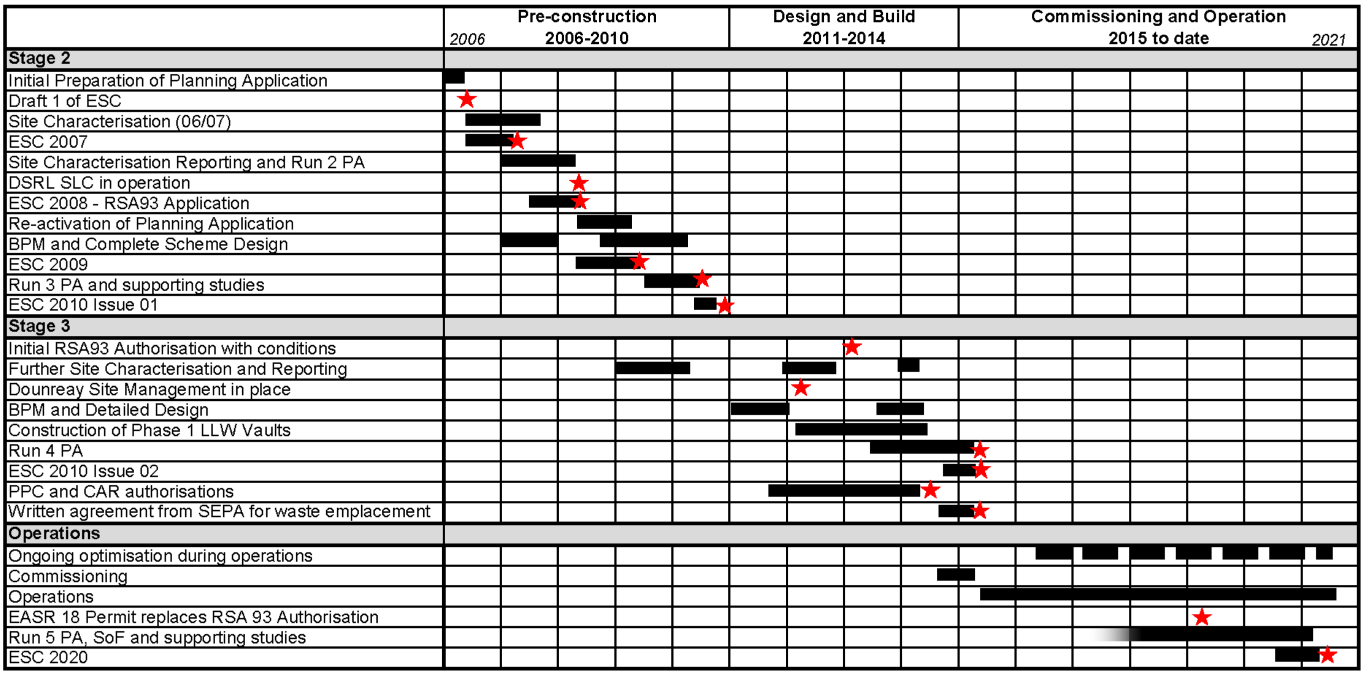

Figure 2.1: Summary of the D3100 project schedule from 2006 (Stage 2 started in October 2005). Red stars indicate key project milestones.

24 The scope of the ESC is defined primarily by the regulatory requirements for authorisation under EASR 18, as set out in the GRA[10] [19]. The requirements of the GRA implement international and national standards and guidance. The GRA sets out requirements for the protection of the public, fauna, flora and the environment from the radioactive wastes disposed of to an authorised facility.

25 The ESC is largely concerned with providing a demonstration that D3100 and its surroundings provide sufficient protection from the radiological hazards, and that management procedures are in place to ensure that the facilities will be safely and appropriately constructed, operated and closed. There is also a requirement in the GRA to demonstrate protection from non-radiological hazards associated with the wastes, for example those related to any hazardous materials potentially present in the radioactive waste. No quantitative performance measures for non-radioactive hazards are provided in the GRA, but similar performance to that required for hazardous waste disposal facilities is expected. Definition and management of hazardous wastes is covered in the Special Waste Amendment (Scotland) Regulations 2004, joint environment agencies technical guidance on the classification of waste (referred to as WM3 [31]), and the Landfill (Scotland)

[10] The 2009 GRA predates EASR 18. Wherever reference is made to RSA 93 in the GRA, the equivalent requirement under EASR 18 is assumed in this ESC.

Amendment Regulations 2013. Characterisation and management of the small non-radiological hazardous component associated with Dounreay LLW is also considered in this ESC.

26 In addition to radiological impacts on the public, flora and fauna, the GRA requires that radionuclides released from a disposal facility do not lead at any time to significant increases in the levels of radioactivity in the accessible environment. This requirement is extended by The Water Environment (Controlled Activities) (Scotland) Regulations 2011 (as amended in 2013 and 2017) (abbreviated as “CAR”), which implement the requirements of the Water Framework Directive and the Groundwater Daughter Directive, including consideration of releases of radionuclides to surface waters and groundwaters [32]. For protection of the water environment, an RSA 93 Authorisation was deemed to be an authorisation granted under CAR [33, Part 2; 19, ¶9.9.1]. Schedule 6, Part 2 of the Environmental Authorisations (Scotland) Regulations 2018 (EASR) [34] amended CAR to reflect the replacement of RSA 93 with EASR 18. This places a legal duty on SEPA to ensure EASR 18 permits are consistent with the requirements of the Water Framework Directive. With regard to the Groundwater Daughter Directive [35], D3100 is exempted from Article 6 concerning the introduction of pollutants by Exemption 3 (b), which states that:

> *(3) (b) Considered to be of a quantity and concentration so small as to obviate any present or future danger of deterioration in the quality of the receiving groundwater.*

and SEPA’s interpretation as set out in [32, Table 1]:

> *(iv) the hazardous pollutant is persistent but its fate in groundwater and the wider environment is understood and the input is environmentally insignificant.*

27 Therefore, protection of groundwater is considered in the D3100 ESC using the results of the same PA undertaken to address the requirements of the GRA with regard to human protection. The performance measures for human protection in the GRA are sufficient to ensure that radionuclide concentrations in groundwater related to releases from D3100 are sufficiently small so as to obviate any danger of deterioration in the quality of the receiving groundwater. Radionuclide concentrations in surface waters and groundwaters related to releases from D3100 are considered in this ESC and are compared to present-day concentrations.

28 During construction and operation, the pumping of groundwater from the excavations also requires a CAR authorisation for abstraction of water. However, this activity is currently outside the EASR 18 regime and is not covered by this ESC; a separate application for such controlled activities was made to SEPA [36], with separate authorisations granted for abstractions from the Phase 1 vaults [37; 38] and in the future from Phase 2 [39; 40]. Similarly, some industrial activities, such as storage and/or crushing of excavated rock to process it for reuse, require a permit from SEPA under the Pollution Prevention and Control (Scotland) Regulations 2012 (PPC). Such activities are again not covered by this ESC; a separate application for the required PPC permits during construction was prepared by DSRL [41]. A PPC permit was granted in 2013 for Phase 1 construction [42; 43], but has since been revoked as it is no longer needed [44]. The preparation of these separate applications is shown in Figure 2.1 by the line titled “PPC and CAR authorisations”.

29 The Dounreay nuclear licensed site adjacent to D3100 has a separate EASR 18 Permit [45], which permits the transfer of waste from the site to D3100 for disposal. Waste is accepted for disposal in D3100 under its EASR 18 Permit [14]. In line with guidance from the environmental regulators on the requirements for release from radioactive substances regulation ("the GRR") [46], DSRL will produce and maintain a Waste Management Plan (WMP) and a Site-Wide Environmental Safety Case (SWESC) to demonstrate that the site meets the required standards for protection of people and the environment. The ESC for D3100 will be a key reference in the site SWESC as it is an adjacent permitted site. Similarly, impacts from the Dounreay site are considered in the D3100 ESC where they are cumulative with those from D3100 and the combined impact needs to be compared to the regulatory requirements. Thus, the D3100 project and the Dounreay site end-state project maintain awareness of, and compatibility between, the two work programmes.

30 During the early stages of the D3100 Project, the creation of the LLW grouting plant was within the scope of the Project. However, the D2179 grout plant has been built on the main Dounreay site and falls within the scope of the site EASR 18 Permit [45], not that of the D3100 Permit [14]. Therefore, the management and impact of the grout plant are outside the scope of this ESC, although ESC requirements on the grouted wasteform contribute to the criteria that waste consignors must meet for waste to be accepted for disposal in D3100.

31 It should be noted that the information presented in this issue of the ESC is not necessarily the final position. The ESC will be a living document up until the time that the EASR 18 Permit for D3100 is revoked. Only the ESC that informs the revocation decision will contain the final position on all topics. Possible future developments are highlighted in the description of the forward programme (see Section 14). However, this issue of the ESC is considered fit for purpose, that is, it is at an appropriate stage of development to support an application to vary the conditions in the extant permit.

2.2 Structure of the Environmental Safety Case

32 The GRA is the primary guidance that details the required content of the ESC. Since the first issue of this ESC in 2006, the GRA has been updated and re-issued. However, the earlier 1997 GRA [20] and the current 2009 GRA [19] have a similar concept in defining a set of Principles, an underlying list of formally defined Requirements, and supporting text providing guidance on additional informal requirements. The Principles, Requirements and additional informal requirements in the 1997 GRA were compiled and grouped according to eight key themes:

- waste characterisation;
- facility design;
- site characterisation;
- quantitative safety assessment;
- additional safety considerations;
- monitoring;

- institutional control; and
- administrative issues.

33 The first issue of this ESC in 2006 was structured in sections to cover each of these eight key themes of requirements, together with sections on the scope of the safety case, the safety strategy and conformity to the principles of radioactive waste management, a summary of the safety case, and a summary of the forward programme.

34 The revised 2009 GRA [19] contains more material than the 1997 GRA. However, aside from the introduction, summary and references, it is split into two parts, with Part 1 being identified as the guidance and Part 2 discussing the national and international context. In the guidance in Part 1, Chapter 4 sets out the Fundamental Protection Objective and the Principles to meet this Objective, Chapter 5 sets out requirements on the process, and Chapter 6 sets out management, radiological and technological requirements. This arrangement is illustrated in Figure 2.2, taken from the 2009 GRA [19, Fig.3.1]. Chapter 7 then sets out a series of requirements on the ESC itself, many of which build on the principles and requirements in Chapters 4 to 6.

35 As is noted in the introduction to the GRA [19, ¶3.2.4], although the GRA is not mandatory, the term "requirement" is used in the GRA to emphasise items that are particularly important from the regulatory perspective and where there is a strong expectation that they will be met. Therefore, to guide the production of the ESC, as for the 1997 GRA, a list of requirements was extracted from the Principles, formally defined Requirements, and supporting text in Chapters 4 to 7 of the 2009 GRA. A mapping between the requirements extracted from the 1997 and 2009 versions of the GRA was undertaken, and was used to update the regulatory crosswalk appendix from ESC 2008 [27] to ESC 2010 [28].

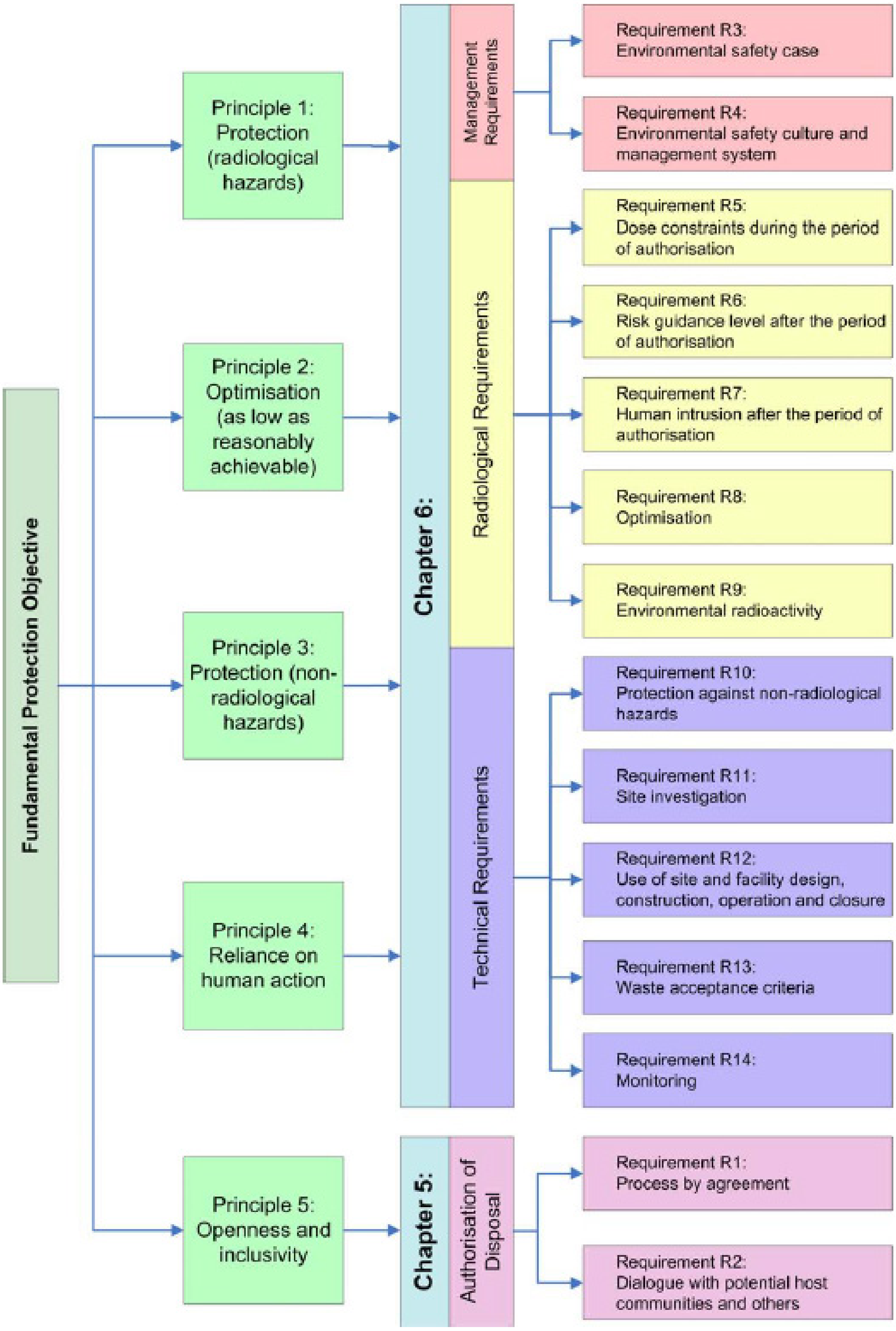

Figure 2.2: Relationship between the Principles and formal Requirements in Part 1 of the 2009 GRA [19, Fig.3.1]. The chapters referred to in the figure are chapters in the GRA, not sections in this ESC – see Figure 2.3.

36 To maintain traceability between iterations of the ESC, the same structure has been used for each. The same eight themes of requirements identified from the 1997 GRA and listed above remain largely valid. However, the "Administrative Issues" section

has been retitled “Programme Management” (Section 12) and the associated text has been sectioned specifically to address the 2009 GRA management requirements (R3 and R4) and the authorisation requirements (R1 and R2) shown in Figure 2.2. The resulting structure of the D3100 ESC is shown in Figure 2.3:

- Section 2 (this section) describes the scope and structure of the ESC using the guidance in the GRA, principally that from [19, Ch.7].
- Section 3 describes the overall strategy adopted by DSRL to achieve environmental safety, the relevant international and national objectives, policy and guidance, and the Principles and Requirements set out in the GRA to fulfil the objectives and policy/legislation.
- Sections 4 to 12 then provide a summary of the information that demonstrates that the requirements extracted from Chapters 5 to 7 of the GRA have been, are being, and will be met. As in previous versions of this ESC, the extracted GRA text on the requirements is listed in a blue box at the start of the main section where the requirements are addressed. However, many requirements are met in several places and, to further improve traceability, a table has been developed that explicitly identifies where the requirements of the GRA are met in the ESC and where further work is ongoing as required or expected. This table, termed a “regulatory crosswalk”, is presented in Appendix B.
- Section 13 gives a summary of the safety case, paying particular attention to the GRA Principles. As the GRA notes [19, ¶3.2.3], if the requirements are fulfilled proportionately to the hazard presented by the waste (as is demonstrated in Sections 4 to 12), then this should ensure that the Principles are properly applied.
- Where further work is identified in Sections 4 to 12, the actions for the forward programme are indicated using a “FP.x” numbering system and green shading. The actions are then summarised in Section 14.

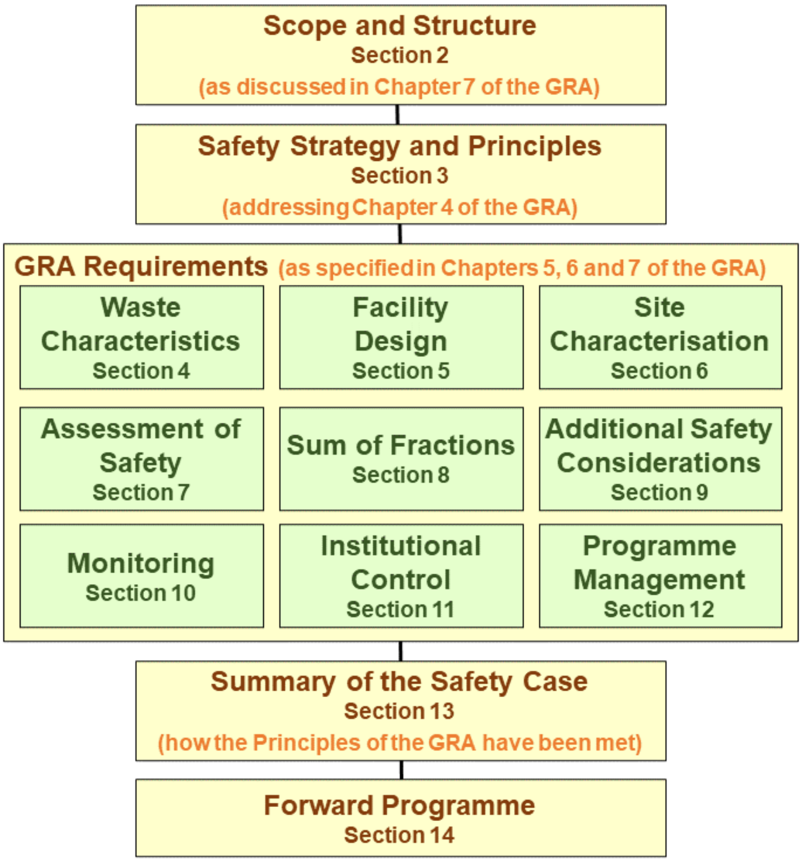

Figure 2.3: Structure of the D3100 ESC with text in red corresponding to chapters in the 2009 GRA [19].

37 The ESC has been developed as a single over-arching document encompassing the main claims and arguments that make up the safety case, with references to supporting documents at a more detailed level where necessary. It is written such that it is stand-alone with regard to all of the key claims, arguments and evidence required to demonstrate safety, but more detail can be found in the supporting references. Both UKAEA/DSRL-produced documents (including technical reports produced during Stage 1 of the D3100 project) and documents in the wider public domain are referenced. Where appropriate, referencing is to specific pages of the referenced document, in order to be clear which part of the document is supporting any particular point made in the safety case.

38 Figure 2.4 illustrates the document hierarchy adopted by DSRL in its document management system for D3100. This ESC is the top-level regulatory submission and is at Tier 1. Other submissions at this level include the planning application. Below the ESC, at Tier 2, DSRL has produced a series of supporting reports consolidating key information. For example, supporting Tier 2 reports for this issue of the ESC that have been substantially revised or are new include the 2020 waste inventory estimate [47], the quantitative Run 5 performance assessment [48], SoF approach (new) [49], site characteristics summary [50], optimisation summary [51], criticality safety assessment [52], management of non-radiological hazards [53], and waste acceptance rules [54]. As for the ESC, the supporting reports will be updated periodically as more information becomes available or is refined through the forward

programme. At Tier 3 are more detailed D3100 project reports that contain interpretations, reviews and plans, and that are consolidated by subject area in the Tier 2 reports. Finally, at Tier 4 are reports containing raw data, records for quality assurance purposes and the like. Also held at Tier 4 in the document management system are third-party reports and scientific literature that are referenced in the ESC, but for which the D3100 project has no ownership or management responsibilities.

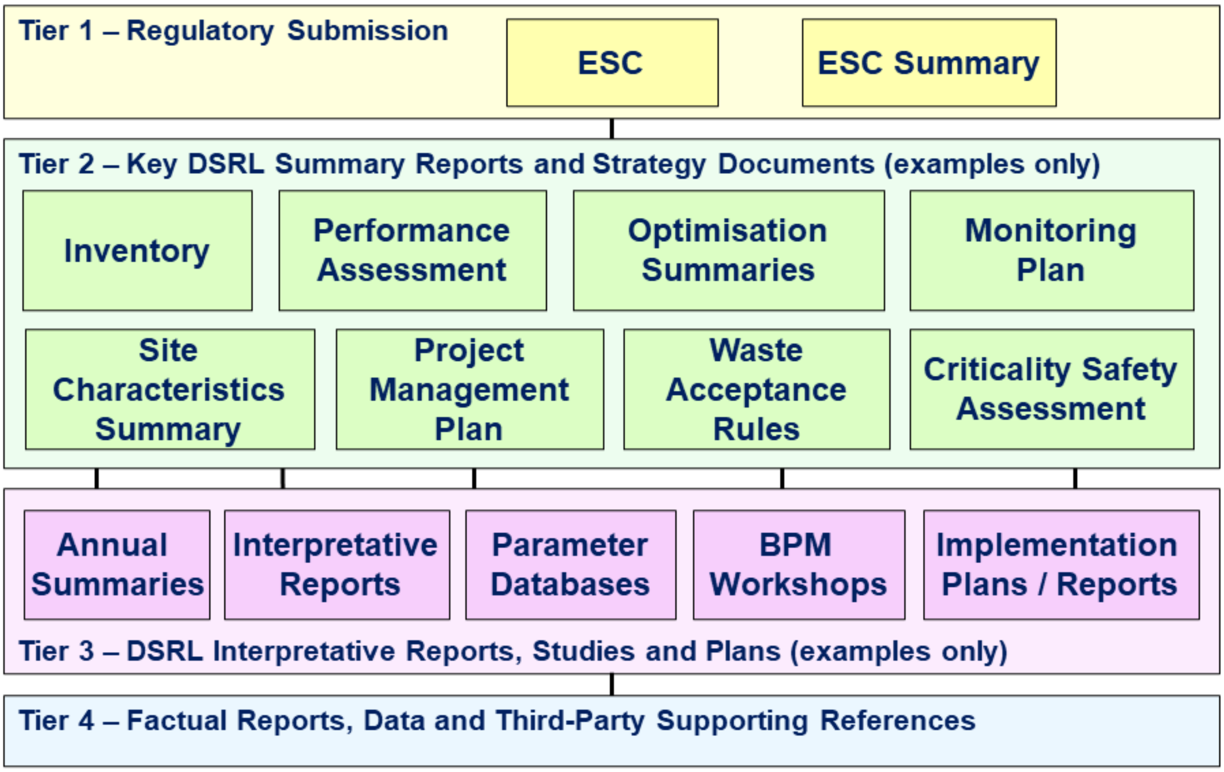

Figure 2.4: Document hierarchy underlying the D3100 ESC. The ESC summary report shown at Tier 1 is not formally part of the regulatory submission, but has been designed and produced by DSRL to inform non-regulatory stakeholders about the ESC.

3 SAFETY STRATEGY AND PRINCIPLES

39 DSRL is committed to applying good technical and management practice for radioactive waste management, in accordance with international and national principles, policy and guidance, and in co-operation with the regulatory authorities and other stakeholders. The international and national principles and policy for radioactive waste management and their context are set out in this section, followed by a discussion of how D3100 complies with them. First, this section summarises the overarching safety strategy for D3100, as required by the GRA [19, ¶7.2.2].

3.1 Safety Strategy

40 In demonstrating compliance with the principles for radioactive waste management, the D3100 project safety strategy requires that safety is paramount and central to the entire D3100 development process. In this context, the term "safety" can be regarded as representing the achievement of appropriate conditions during construction, operations and in the long-term, so as to provide an adequate and optimised level of protection to workers, members of the public, and the environment from hazards. Key measures adopted by DSRL and the D3100 project in implementing the safety strategy to arrive at the disposal system concept represented by D3100, and to support its continued operation, include:

- Sound and open process (e.g. flexible, step-by-step development, extensive stakeholder dialogue, and peer review of key documents).
- Positive environmental safety culture supported by a management system that ensures effective leadership, proper arrangements for policy and decision making, a suitable range of competencies, provision of sufficient resources, a commitment to continuous learning, and proper arrangements for succession planning and knowledge management.
- Use of robust and demonstrable safety measures (e.g. proven, well understood engineering technology, and long-term stability of the site).
- Strength in depth in the design through the use of multiple barriers and no sole reliance on single components or processes for regulatory compliance.
- Reliance on passive safety measures in the long-term (initially, although passive safety barriers are in place, safety is assured by active measures, such as monitoring and surveillance during an institutional control period; in the longer term, after active measures are withdrawn, safety is inherent in the disposal system design, and it is not reliant on human actions).
- Structured, transparent and traceable demonstration of environmental safety during both the authorisation and post-authorisation periods, using internationally recognised assessment methods and tools.

41 Evidence for the implementation of these measures, namely the activities and assessments undertaken to realise the safety strategy, is presented in this ESC and other D3100 project documents, such as the BPEO [7] and BPM assessments, operational nuclear safety case [55], and management plans and procedures.

42 The disposal system fulfils three safety functions in order to achieve safety in both the short-term and long-term:

- Isolation. Isolating the waste from humans and the environment.
- Containment. Preventing the release of contaminants from the facilities before they decay or break down into harmless materials.
- Delay and attenuation (retardation). Retaining contaminants – once released from the wastes – within the disposal system and reducing their rate of release to the human environment.

43 The attainment of these safety functions by D3100 is demonstrated in this ESC and is summarised in Section 13 and in the Executive Summary. The summaries fulfil the requirement of the GRA in describing the safety strategy in terms of the key environmental safety arguments presented in the ESC and how these arguments are supported by lines of reasoning and underpinning evidence.

3.2 International Principles for Radioactive Waste Management

44 International principles, standards and guidance for radioactive waste management are reviewed here in terms of the organisations responsible for them.

3.2.1 International Atomic Energy Agency (IAEA)

45 The IAEA is the main inter-governmental forum for scientific and technical co-operation in the nuclear field. Its pronouncements have no legal jurisdiction. However, Member countries commit themselves to complying with its standards and recommendations. The UK is a signatory to the IAEA Joint Convention on the Safety of Spent Nuclear Fuel and the Safety of Radioactive Waste Management [56]. Within the IAEA Safety Standards Commission and Committees, the Waste Safety Standards Committee (WASSC) is responsible for the development, review and revision of the IAEA standards relating to radioactive waste safety (i.e. waste management, waste treatment and safety of disposal facilities). These standards implement the basic safety objective and safety principles, as set out in the IAEA Safety Fundamentals [57] and reproduced in Table 3.1.

46 Below the top level of the IAEA Safety Fundamentals, the IAEA standards are established in Safety Requirements and Safety Guides. The standards are not legally binding in the UK, but they represent good practice and are reflected in UK legislation and guidance such as the GRA. The IAEA Safety Requirements and Safety Guides that are particularly relevant to defining good practice with respect to the construction and operation of D3100 include:

- Safety Requirements for Disposal of Radioactive Waste [23].
- Safety Guide for the Safety Case and Safety Assessment for Disposal of Waste [24].
- Safety Guide specifically for near-surface disposal [25].
- Safety Guide for the classification of radioactive waste [58].

- Safety Series on Siting of Near Surface Disposal Facilities [59]. This preceded the safety standards, but was relevant during the siting of D3100. It has now been replaced by an appendix in the Safety Guide for near-surface disposal [25].
- Safety Requirements for Governmental, Legal and Regulatory Framework for Safety [60].
- Safety Requirements for Leadership and Management for Safety [61].
- Safety Guide for the Management System for the Disposal of Radioactive Waste [62].
- Transport Regulations [63].

Table 3.1: The IAEA Fundamental Safety Objective and Principles for radiological protection [57].

Safety Objective.
The fundamental safety objective is to protect people and the environment from harmful effects of ionising radiation.
Principle 1: Responsibility for safety.
The prime responsibility for safety must rest with the person or organisation responsible for facilities and activities that give rise to radiation risks.
Principle 2: Role of government.
An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained.
Principle 3: Leadership and management for safety.
Effective leadership and management for safety must be established and sustained in organisations concerned with, and facilities and activities that give rise to, radiation risks.
Principle 4 Justification of facilities and activities.
Facilities and activities that give rise to radiation risks must yield an overall benefit.
Principle 5: Optimisation of protection.
Protection must be optimised to provide the highest level of safety that can be reasonably achieved.
Principle 6: Limitation of risk to individuals.
Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm.
Principle 7: Protection of present and future generations.
People and the environment, present and future, must be protected against radiation risks.
Principle 8: Prevention of accidents.
All practical efforts must be made to prevent and mitigate nuclear or radiation accidents.
Principle 9: Emergency preparedness and response.
Arrangements must be made for emergency preparedness and response in case of nuclear or radiation incidents.
Principle 10: Protective actions to reduce existing or unregulated radiation risks.
Protective actions to reduce existing or unregulated radiation risks must be justified and optimised.

47 The D3100 disposal facilities and this ESC have been developed in compliance with IAEA standards and guidance. In particular, the IAEA classification of radioactive waste defines LLW as [58, ¶2.2(4)]:

> *"Waste that is above clearance levels, but with limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near surface facilities."*

48 The IAEA also produces numerous technical reports on particular issues. These have been used extensively by the D3100 project and are referenced as appropriate throughout this ESC. In particular, the IAEA has instigated programmes to improve long-term safety assessment methodologies for near-surface disposal facilities. The ISAM (Improvement of Safety Assessment Methodologies for Near-Surface Waste Disposal Facilities – ISAM [64]) programme was instigated during the first stage of the D3100 project and has continued since under several follow-on programmes. The D3100 safety assessment presented in Section 7 of this ESC is consistent with the guidance from these programmes, and DSRL staff and D3100 project contractors have participated in the IAEA programmes.

3.2.2 International Commission on Radiological Protection (ICRP)

49 The ICRP is an independent Registered Charity established to advance, for the public benefit, the science of radiological protection, in particular by providing recommendations and guidance on all aspects of protection against ionising radiation. It is, in effect, an independent international network of specialists in various fields of radiological protection. The ICRP has defined a system of radiation protection through recommendations based on three principles [65, §5.6]:

- Justification – no practice shall be adopted unless it produces sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes.
- Optimisation – the magnitude of the doses, the number of people exposed, and the likelihood that potential exposures will occur shall be kept as low as reasonably achievable, economic and social factors being taken into account (ALARA).
- Limitation – limits are placed on the dose and risk to individuals so that they do not exceed a value that is considered acceptable.

50 The principles represent quite general aims and underlie all radiation protection activities. They are reflected in other international principles and guidance, such as those set by the IAEA and the European Commission, and in the GRA. Compliance with the GRA ensures compliance with the ICRP principles.

51 The ICRP has also developed guidance on the application of its principles in specific areas, including radioactive waste disposal (e.g. [66; 67]). This ICRP guidance has been considered by the UK regulators in the setting of radiological protection targets in the GRA [19], and in advice given during production of the GRA by the Health

Protection Agency[11] (HPA) on radiological protection objectives for solid radioactive waste disposal [68]. Therefore, compliance with the GRA also ensures compliance with the ICRP guidance on the application of its principles.

3.2.3 European Commission (EC) / European Union (EU)

52 The EURATOM Treaty was established in 1957 to promote the peaceful use of nuclear technology in Europe. A key component of the Treaty in this context is Article 37, which requires Member States to assess the potential contamination of other Member States' airspace, water and food-chain owing to any of a prescribed list of activities employing nuclear technology [69, Article 37]:

> *"Each Member State shall provide the Commission with such general data relating to any plan for the disposal of radioactive waste in whatever forms will make it possible to determine whether the implementation of such plan is liable to result in the radioactive contamination of the water, soil or airspace of another Member State. The Commission shall deliver its opinion within six months, after consulting the group of experts referred to in Article 31."*

53 In the Dounreay context, DSRL is required to prepare documentation in support of an Article 37 submission for planned radioactive waste disposals or discharges. SEPA undertakes a technical review of such documentation on behalf of the Scottish Government, and then the documentation is submitted by the UK Government[12] to the EC. DSRL prepared an Article 37 submission in 2010 in conjunction with the application to SEPA for authorisation of D3100 [70]. The EC provided an opinion that the D3100 disposal facilities were "not liable to result in a radioactive contamination of the water, soil or airspace of another Member State" in December 2011 [71], which was acknowledged in SEPA's decision document on the original RSA 93 application for D3100 [72].

54 In October 2010, the EC made a recommendation on application of Article 37 of the Euratom Treaty [73]. This states that, for modification of plans for disposal of radioactive waste on which a decision has already been given by the EC under the terms of Article 37, the submission of "general data" to the EC is not required (1) if a new authorisation/licence is not required, or (2) the modification does not change, or results in more restrictive, authorised limits and associated requirements, and the potential consequences of unplanned releases are unchanged or decreased. If the authorised limits or the associated requirements for the disposal of radioactive waste are less restrictive than in the existing plan, or if the potential consequences of unplanned releases are increased, then a submission of "general data" containing at least the information set out in Annex V of the recommendation is necessary. The application being made here to apply a risk-based approach to radionuclide limits in

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11 The HPA was incorporated into Public Health England (PHE) on 1 April 2013. PHE is currently (August 2020) in the process of becoming part of a new organisation, the National Institute for Public Health (NIPH). The equivalent organisation in Scotland is Public Health Scotland – this succeeded Health Protection Scotland (formed in 2005) in April 2020.

12 The Article 37 submission for D3100 was made in 2011 by the Department of Energy and Climate Change (DECC). DECC became part of the Department for Business, Energy and Industrial Strategy (BEIS) in July 2016.

the D3100 Permit continues to limit acceptable waste to LLW, but does increase flexibility in the proportions of radionuclides that can be accepted.

55 As the UK has left the EU (and the Euratom Treaty), and the transition period ended on 31 December 2020, the requirement for the UK to submit information to the EC on plans for the disposal of radioactive waste no longer applies. The UK has consulted with stakeholders on alternative measures to keep neighbouring states informed of radioactive waste disposal plans in the UK [74; 75]. In England, the Department for Business, Energy and Industrial Strategy (BEIS) intends to make a Statutory Instrument amending the Environmental Permitting (England and Wales) Regulations 2016 (EPR 16) so that, when an operator applies for an environmental permit, the Environment Agency will consider whether the planned disposal of radioactive waste is liable to result in transboundary radioactive contamination. As part of their consideration, the Environment Agency will invite views through public consultation and BEIS will notify international partners of the permit application [76]. It is understood that Scottish Government and SEPA intend to implement a similar process via the equivalent legislation to EPR 16, namely EASR 18 [77]. DSRL and SEPA are in discussion with Scottish Government and BEIS about the process to follow.

56 A number of EC Directives and Regulations have been made under the EURATOM Treaty, of key importance being the Basic Safety Standards (BSS) Directives. Council Directive 96/29/EURATOM of 13 May 1996 [78] lays down BSS for the protection of the health of workers and the general public against the dangers arising from ionising radiation. The EC BSS are consistent with the BSS set by international organisations [79] and are required to be implemented in the European Union Member States. The EC BSS were revised in 2014 [80], maintaining consistency with international consensus [81]. The 2014 BSS revisions have been implemented in UK and Scottish legislation, but implementation has not affected the D3100 safety strategy presented in this ESC. The main provisions of the BSS are implemented in Scotland via EASR 18, the Nuclear Installations Act 1965, the Ionising Radiations Regulations 2017, the Ionising Radiation (Basic Safety Standards) (Miscellaneous Provisions) Regulations 2018, the Radiation (Emergency Preparedness and Public Information) Regulations (REPPIR) 2019, the Justification of Practices Involving Ionising Radiation Regulations 2004 and its 2018 amendment, and the Regulatory Reform (Specification of Basic Safety Standards Directive) (Scotland) Order 2018 (and their EU Exit amendments). By complying with the national legislation, D3100 also complies with the EC Directives.

3.2.4 Nuclear Energy Agency (NEA)

57 The NEA is a semi-autonomous body within the Organisation for Economic Co-operation and Development (OECD). The primary objective of the NEA is to promote co-operation among the governments of its Member countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source. The mission of the NEA's Radioactive Waste Management Committee (RWMC) is "*to assist Member Countries in developing safe management strategies and technologies for spent nuclear fuel, long-lived waste and waste from the decommissioning of nuclear facilities.*" Although much of the programme of the RWMC is concerned with deep geological disposal of long-lived waste, many of the

general principles, methodologies and problems addressed are also of relevance to near-surface disposal. The conduct of the safety assessment and the development of this ESC have taken account of recommendations from the NEA (e.g. [21; 24; 82]).

3.3 UK National Policy and Strategy for LLW Management

58 Policy in Scotland and the rest of the UK on radioactive waste management has been developed separately for LLW and for higher activity wastes. With regard to the latter, the Scottish Government has consulted on and determined a policy for the management of Intermediate Level Waste (ILW) and LLW that is "not currently suitable for disposal in existing LLW facilities" [83]. An implementation strategy for Scottish Government policy (long-term management in near-surface facilities located as near as possible to the site where the waste was produced), was published in 2016 [84]. Therefore, DSRL currently plans to store higher-activity waste on the Dounreay site pending the availability of a suitable Scottish waste disposal facility. In England and Wales, as part of the "Managing Radioactive Waste Safely" programme, a national framework for implementing geological disposal of higher activity wastes is being taken forward [85]. This includes a 2014 policy statement on implementing geological disposal [86], updated in 2018 to detail the consent-based approach to working in partnership with communities to find a disposal site [87].

59 However, the LLW to be consigned to D3100 at Dounreay falls outside of these programmes. Instead, for LLW, the UK Government and devolved administrations published a LLW policy document in 2007 [3]. The 2007 LLW policy replaced or amended those parts of the 1995 UK radioactive waste management policy (Cm2919 [88]) concerned with LLW. The policy was developed following consultation by the Department for Environment, Food and Rural Affairs (Defra) on the management of all UK LLW. The 2007 policy required the NDA to develop a complementary strategy for the management of solid low level radioactive waste in the UK nuclear industry. This strategy was first produced in 2010 and was updated in 2016 by UK Government (DECC) [89], following review and public consultation. The three strategic themes promoted in the 2007 policy remain unchanged in the 2016 strategy: the application of the waste hierarchy; best use of existing LLW management assets; and the need for new fit-for-purpose waste management routes. The responsibility within the UK Government for LLW policy now lies with BEIS.

60 The LLW policy and strategy [3; 89] are not prescriptive, but recognise that the solution for each LLW management need must be decided on a case-by-case basis. All nuclear licensed sites are expected to have a plan for the management of their LLW that is part of a wider integrated waste management strategy, and is compatible with proposed site end-states. Further, the management plans should be based on a formal assessment (e.g. BPEO-type analysis) of all of the practicable options for the long-term management of the waste, taking into account safety and environmental impacts, and social and economic factors. The management plan should use a risk-informed approach to ensure safety and protection of the environment, be in accordance with the waste management hierarchy principles, and include consideration of the proximity principle and transport issues. The policy and strategy provide examples of practicable options for LLW management for consideration. The documents also state that disposal to an appropriately

engineered facility, either below or above ground, with no intent to retrieve, should be the end point for LLW that remains following the application of the waste management hierarchy. DSRL has complied with these requirements in the development of its LLW management strategy.

61 The LLW policy defines the activity limits of LLW, as set out in paragraph 2. Since the start of the D3100 project, the exemption regime for authorisation under RSA 93 has been revised [90; 91] and then again when RSA 93 was superseded by EASR 18 [34, Sch.8]. However, DSRL does not expect that the revisions will have a significant impact on the inventory for D3100, although it is now clearer what are clean and exempt wastes for avoiding unnecessary consignments as LLW. DSRL has discussed application of the LLW definition with SEPA. The established practice on nuclear sites for reporting radionuclide activities is to exclude the activities of short-lived daughters (those less than 3 months) where these daughters are in secular equilibrium with the parent radionuclides. In the long-term, SEPA plans to raise this for consideration in the next revision of national policy documentation and the EASR 18 Standard Conditions [92, §8]. However, in the short-term, explicit clarification of this is being sought by DSRL from SEPA, for example, through a bespoke condition and/or definition in the revised Permit [93; 92, §8]. Clarification is also sought that, as the conditioning grout and container are part of the consigned waste received at the D3100 gate, it is the gross weight of the waste package that should be used to determine that disposals to D3100 are LLW.

62 An additional aspect of the LLW policy document [3] is the recognition that large volumes of very low activity LLW (VLLW) might be disposed of to specified landfills rather than to specialised disposal facilities. DSRL has not attempted to retrospectively apply the definition of high-volume VLLW given in the LLW policy to the waste streams at Dounreay. However, DSRL's strategy for LLW management at Dounreay is consistent with the policy, in as much as it is based upon the segregation of LLW into two groups (LLW and Demolition LLW), and the disposal of these LLW groups will be to separate facilities designed as appropriate to the different levels of risk the wastes present.

63 The LLW strategy [89] also highlights that opportunities to safely manage wastes at the boundary between LLW and Higher Activity Waste (HAW) as LLW should be considered within waste management decision making. The D3100 Permit limits the activity of acceptable wastes to that of the LLW definition and, in consulting with the local community during development of the D3100 project, DSRL made a commitment to only dispose of LLW from the Dounreay site [16; 94; 95; 96]. However, consistent with the national strategy, DSRL is reviewing the potential for disposal of some LLW/HAW boundary streams in D3100 where those streams may be recategorised as LLW pending further characterisation or may meet the LLW activity definition following a period of decay storage [47].

64 The NDA, UK government, safety and environmental regulators, and planning authorities, are working together to explore options for more proportionate regulatory control (PRC) of nuclear sites as they progress towards their end state. This has led to a proposal from UK government to amend the legislative framework that applies to nuclear sites [17; 97] and enable more streamlined regulation during the final stages of decommissioning and clean-up. The proposed amendment would enable

site operators to optimise end states on a site-by-site basis, in consultation with local stakeholders and under regulation by the relevant environment agency. Pressure on Parliamentary time has delayed the necessary amendments to primary legislation [2, p.40], but work is ongoing to identify secondary legislation and guidance (such as the GRR; see paragraph 29) that will be required. As noted in paragraph 13, as a result of the proposed amendments the Dounreay site end state is under review. Changes in the plans for the site end state could impact the wastes requiring disposal in D3100. For example, opportunities may be identified to reuse lightly contaminated soil and building demolition rubble on the Dounreay site, instead of disposal as Demolition LLW in D3100. This would be consistent with the waste hierarchy, minimising waste creation and the use of new materials. This is acknowledged as a current uncertainty in the inventory estimate for D3100 (e.g. see paragraphs 89-91). Any releases from proposed on-site disposals and their potential for cumulative impacts to D3100 receptors must also be considered in future versions of this ESC (see paragraph 29).

65 In addition to NDA support, the D3100 project has received support from the Scottish Government. In May 2005, the Scottish Government issued a Direction to SEPA to refuse UKAEA's 2002 application to transfer LLW from Dounreay to the LLWR for disposal [6]. The Explanatory Note to the Direction by Scottish Ministers endorsed UKAEA's strategy (now DSRL's strategy) for disposal of Dounreay's LLW at Dounreay [6, ¶5]. Subsequent discussions with the Scottish Government by SEPA [98, p.3] have clarified that it is Scottish Government policy for there to be a LLW disposal facility at, or near, the Dounreay nuclear licensed site.

3.4 Compliance with Policies and Principles for Radioactive Waste Management

3.4.1 Environmental protection

66 The Statutory Guidance issued to SEPA in relation to the authorisation of radioactive waste discharges under RSA 93 [99] (now under EASR 18), and the subsequent UK strategy for radioactive discharges [100] (and its later 2018 review [101]), require consideration of both BPEO and Best Practicable Means (BPM). This dual requirement is consistent with an interpretation of BPEO that is concerned with identifying and justifying a preferred (best practicable) overall management approach, taking account of a broad range of strategic considerations [102]. This is different from BPM, which relates to optimisation of the selected option from the perspective of radiological protection, and is concerned with the detailed refinement of design and operational conditions. The environment agencies view BPM as a means of engendering a culture of environmental protection with respect to the management of radioactive substances [103, p.ii]. The use of BPM, alongside the use of detailed assessments, is intended to ensure that radiological impacts to people associated with a preferred strategy are as low as reasonably achievable (ALARA), social and economic factors being taken into account [103]. This is consistent with the principles of the ICRP and the requirements of the BSS [102]. Later guidance explicitly discusses the application of BPM to solid waste disposal activities [104]. In particular, it is noted that BPM should be applied to minimise radioactive discharges from a facility to the environment, but BPM does not apply to minimising the total

activity of radioactive waste consigned to the facility [104, §4.5]. More recent guidance from SEPA [105, ¶1.1] explains that EASR 18 uses the term optimisation instead of ALARA, with optimisation defined in EASR 18 as [34, Sch.8, ¶3]:

> *"keeping the magnitude of individual doses, the likelihood of exposure and the number of individuals exposed as low as reasonably achievable taking into account the current state of technical knowledge and economic and social factors".*

67 The GRA [19, ¶8.8.6] also notes that BPM and BPEO guidance should be taken into account when considering optimisation in developing a disposal facility for solid radioactive waste.

68 In Stage 1 of the Dounreay LLW management project, UKAEA undertook a BPEO study to support the decision on a long-term management solution for Dounreay's LLW [7]. Conduct of a BPEO study is consistent with UK policy, and the chosen strategy was development of new disposal facilities at Dounreay. This option is consistent with UK and Scottish radioactive waste management policy, as outlined in the previous section. In 2009, the BPEO was reviewed and assessed as still valid [106]. In subsequent stages of the project, referred to collectively as the D3100 project in this ESC, DSRL has undertaken numerous BPM and optimisation studies to develop and optimise the selected strategy and the planning, construction and operation of D3100. Optimisation activities are summarised periodically by DSRL, with an update produced in 2020 [51], and are also summarised in Section 5 of this ESC.

3.4.2 Radiological protection

69 The GRA [19, Ch.4] contains a fundamental protection objective for solid radioactive waste disposal, and five overarching principles consistent with international standards:

- **Fundamental protection objective.** Ensure that all disposals of solid radioactive waste to facilities on land are made in a way that protects the health and interests of people and the integrity of the environment, at the time of disposal and in the future, inspires public confidence and takes account of costs.
- **Principle 1: Level of protection against radiological hazards at the time of disposal and in the future.** Solid radioactive waste shall be disposed of in such a way that the level of protection provided to people and the environment against the radiological hazards of the waste both at the time of disposal and in the future is consistent with the national standard at the time of disposal.
- **Principle 2: Optimisation (as low as reasonably achievable).** Solid radioactive waste shall be disposed of in such a way that the radiological risks to individual members of the public and the population as a whole shall be as low as reasonably achievable under the circumstances prevailing at the time of disposal, taking into account economic and societal factors and the need to manage radiological risks to other living organisms and any non-radiological hazards.

- **Principle 3: Level of protection against non-radiological hazards at the time of disposal and in the future.** Solid radioactive waste shall be disposed of in such a way that the level of protection provided to people and the environment against any non-radiological hazards of the waste both at the time of disposal and in the future is consistent with that provided by the national standard at the time of disposal for wastes that present a non-radiological but not a radiological hazard.
- **Principle 4: Reliance on human action.** Solid radioactive waste shall be disposed of in such a way that unreasonable reliance on human action to protect the public and the environment against radiological and any non-radiological hazards is avoided both at the time of disposal and in the future.
- **Principle 5: Openness and inclusivity.** For any disposal of solid radioactive waste, the relevant environment agency shall: establish ways of informing interested parties and the public about regulatory goals, processes and issues; and consult in an open and inclusive way.

70 The GRA principles reflect national and international policy, including the high-level principles of the IAEA (Table 3.1) and ICRP. Principle 1, as set out above, is consistent with the IAEA principles for limitation of radiological exposures (Principles 6 and 7) and the ICRP principle on optimisation of protection and application of dose limits. Principle 2 on optimisation is consistent with the ICRP and IAEA principles on optimisation. Principle 3 extends the protection objective to cover non-radiological hazards. Principle 4 is consistent with the concept of sustainable development (meeting the needs of the present without compromising the ability of future generations to meet their own needs). Principle 5 applies to the work undertaken by SEPA and reflects IAEA Principle 2 on the role of government.

71 As noted in paragraphs 34 and 35, the GRA sets out a number of expectations or requirements to demonstrate compliance with the overarching principles. Fourteen requirements are formally set out in the GRA (Table 3.2), and these are identified in this ESC using the nomenclature Requirement R1 to R14. The text of the GRA under the Requirements and the text in Chapter 7 of the GRA on the content of the ESC then provide a series of further, more detailed requirements. Sections 4 to 12 of this ESC show how D3100 meets the detailed requirements of the GRA, including the formally defined Requirements listed in Table 3.2. The key sections of this ESC that demonstrate that the D3100 project meets the relevant GRA Requirements are indicated in Table 3.2, but note that many GRA requirements are met in several places in the ESC - the GRA crosswalk in Appendix B explicitly identifies where the requirements of the GRA are met. By meeting the detailed requirements, D3100 also complies with the GRA principles and, therefore, national and international waste management policy and principles. It is the regulators' intention [19, ¶3.5.1] that "*demonstration of conformity with the requirements should be sufficient to establish conformity with the principles*." This compliance is reinforced in the summary of the safety case in Section 13.

Table 3.2: Requirements R1 to R14 set out in the UK regulatory guidance for authorisation of near-surface disposal facilities on land for solid radioactive wastes (the GRA) [19]. The main section where the requirements are addressed is indicated, but reference should be made to the regulatory crosswalk table in Appendix B for identification of all relevant sections.

Requirement R1: Process by agreement *(Section 12.2)*
The developer should follow a process by agreement for developing a disposal facility for solid radioactive waste.
Requirement R2: Dialogue with local communities and others *(Section 12.4)*
The developer should engage in dialogue with the planning authority, local community, other interested parties and the general public on its developing environmental safety case.
Requirement R3: Environmental safety case *(this document)*
An application under RSA 93 relating to a proposed disposal of solid radioactive waste should be supported by an environmental safety case.
Requirement R4: Environmental safety culture and management system *(Section 12.1)*
The developer/operator of a disposal facility for solid radioactive waste should foster and nurture a positive environmental safety culture at all times and should have a management system, organisational structure and resources sufficient to provide the following functions: (a) planning and control of work; (b) the application of sound science and good engineering practice; (c) provision of information; (d) documentation and record-keeping; (e) quality management.
Requirement R5: Dose constraints during the period of authorisation *(Section 7.7.1)*
During the period of authorisation, the effective dose from the facility to a representative member of the critical group should not exceed a source-related dose constraint and a site-related dose constraint.
Requirement R6: Risk guidance level after the period of authorisation *(Section 7.7.2)*
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 (i.e. 1 in a million per year).
Requirement R7: Human intrusion after the period of authorisation *(Section 7.7.2)*
The developer/operator of a near-surface disposal facility should assess the potential consequences of human intrusion into the facility after the period of authorisation on the basis that it is likely to occur. The developer/operator should, however, consider and implement any practical measures that might reduce the chance of its happening. The assessed effective dose to any person during and after the assumed intrusion should not exceed a dose guidance level in the range of around 3 mSv/year to around 20 mSv/year. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of years (prolonged exposures), while values towards the upper end of the range are applicable to assessed exposures that are only short term (transitory exposures).

Requirement R8: Optimisation *(Section 5.5)*
The choice of waste acceptance criteria, how the selected site is used and the design, construction, operation, closure and post-closure management of the disposal facility should ensure that radiological risks to members of the public, both during the period of authorisation and afterwards, are as low as reasonably achievable (ALARA), taking into account economic and societal factors.
Requirement R9: Environmental radioactivity *(Section 7.9)*
The developer/operator should carry out an assessment to investigate the radiological effects of a disposal facility on the accessible environment both during the period of authorisation and afterwards with a view to showing that all aspects of the accessible environment are adequately protected.
Requirement R10: Protection against non-radiological hazards *(Section 7.10)*
The developer/operator of a disposal facility for solid radioactive waste should demonstrate that the disposal system provides adequate protection against non-radiological hazards.
Requirement R11: Site investigation *(Section 6)*
The developer/operator of a disposal facility for solid radioactive waste should carry out a programme of site investigation and site characterisation to provide information for the environmental safety case and to support facility design and construction.
Requirement R12: Use of site and facility design, construction, operation and closure *(Section 5.2)*
The developer/operator of a disposal facility for solid radioactive waste should make sure that the site is used and the facility is designed, constructed, operated and capable of closure so as to avoid unacceptable effects on the performance of the disposal system.
Requirement R13: Waste acceptance criteria *(Section 4.4)*
The developer/operator of a disposal facility for solid radioactive waste should establish waste acceptance criteria consistent with the assumptions made in the environmental safety case and with the requirements for transport and handling, and demonstrate that these can be applied during operations at the facility.
Requirement R14: Monitoring *(Section 10)*
In support of the environmental safety case, the developer/operator of a disposal facility for solid radioactive waste should carry out a programme to monitor for changes caused by construction, operation and closure of the facility.

4 WASTE CHARACTERISTICS, QUANTITIES AND ACCEPTANCE

72 This section addresses the detailed requirements in the GRA in relation to the characteristics of the wastes to be disposed of in D3100. The EASR 18 Permit, the planning consent and the long-standing objectives of the D3100 project require that only solid LLW and only LLW from the Dounreay nuclear licensed site and the Vulcan site are disposed of. Therefore, these boundary conditions set the types of waste that the facilities will accept and provide a good basis for deriving a projection of the likely inventory. The characteristics of the waste and current projections of the inventory are covered first in this section.

73 The consignment and acceptance of the wastes are two separate processes, and separate authorisations for both processes are required from SEPA, one for the consignor under the EASR 18 Permit for the Dounreay licensed site (Permit EAS/P/117600 [45]), and one for the operator of D3100 under its EASR 18 Permit (Permit EAS/P/1173599 [14]). The EASR 18 Permit for D3100 sets out Waste Acceptance Criteria (WAC) to be applied by DSRL (as the operator of D3100) to accept wastes from the Dounreay licensed site (the consignor to D3100). How the D3100 waste acceptance process is fit-for-purpose for ensuring that waste consigned to D3100 meets these “Authorised” WAC, and other acceptance requirements imposed by DSRL, is discussed at the end of this section.

74 Note that throughout Sections 4 to 12, the relevant GRA requirements, identified by the paragraph number of the GRA from which they are taken, are reproduced in the blue boxes at the beginning of the main section in the ESC that addresses them. However, it should be noted that some requirements are addressed further or in part in several other sections as well. Where this is the case, the regulatory crosswalk in Appendix B provides the links from the requirement to each section.

4.1 Waste Characteristics

GRA 7.2.6(b)	The ESC should describe all aspects that may affect environmental safety, including the characteristics of the waste (including any waste treatment and conditioning before disposal).

75 As noted above, the boundary conditions applied to D3100 are that they will only accept solid LLW for disposal, and only from the Dounreay nuclear licensed site and adjacent Vulcan site. Government policy defines LLW as radioactive waste having a radioactive content not exceeding 4 GBq te^{-1} of alpha activity or 12 GBq te^{-1} of beta/gamma activity [3]. The lower limits for LLW, below which wastes cease to require a permit for disposal, are set out in EASR 18 [34, Sch.8, Tab.2].

76 Radioactive waste is produced by various projects and facilities on the Dounreay site. As noted in Section 1, for D3100 and for waste management purposes on the licensed site, DSRL distinguishes between:

- Operational and decommissioning LLW, as defined in UK LLW management policy [3]. This is radioactive waste within the UK LLW category limit, but excluding the Demolition LLW streams described below. Operational wastes produced at Dounreay are historical and this waste is now in storage. All current and future LLW arisings at Dounreay are from decommissioning and remediation activities, including retrieval of the LLW Pits.

- Demolition LLW. A DSRL-defined group of LLW streams comprising unconditioned material including, but not restricted to, concrete, bricks, metals, stone, sand and soil, with low radiological and non-radiological hazards. The radioactive content of Demolition LLW does not exceed 0.01 GBq te^{-1} of alpha or 0.40 GBq te^{-1} of beta/gamma activity. *(This waste category definition is now specified in the D3100 Permit.)*

77 Waste producers on the Dounreay licensed site use the Dounreay Waste Manual [107] to determine whether the waste falls within the LLW category and to decide on appropriate waste management steps. It is important to note that the Waste Manual and the development of D3100 are part of an integrated waste strategy at Dounreay. In implementing the waste strategy, DSRL is committed to waste minimisation (e.g. [7, ¶E18; 108]), consistent with the primary, or top-level step, of the waste management hierarchy. This applies to both radioactive and non-radioactive materials. There is both an ongoing DSRL commitment and a regulatory requirement through the Scottish Government's Zero Waste Plan [109] to implement the waste hierarchy within the waste management system. The DSRL Waste Manual, D3100 waste acceptance criteria and D3100 EASR 18 Permit all require demonstration by consignors of Best Practical Means (BPM) and application of the waste hierarchy during the generation of the wastes, which ensures that wastes are only consigned to D3100 where this is the most appropriate management route. Waste characterisation is a key part of this process and DSRL has recently strengthened its management though implementation of a new DSRL standard on waste characterisation [110] and a characterisation process procedure [111].

78 Waste assessed as LLW requiring disposal is currently consigned by the waste producers on the Dounreay licensed site to the DSRL Waste Operations directorate for processing and interim storage. All solid LLW must be packaged appropriately and/or loaded into containers that have been approved for use by site Waste Operations. Waste is consigned by the site under the following categories for which Conditions for Acceptance (CfA) are set [112]:

- **Compactable LLW.** LLW packaged in standard mild steel 200-litre drums (C-bins) suitable for high-force compaction at the D8570 Waste Receipt, Assay, Characterisation and Supercompaction (WRACS) facility. Solid LLW consigned to C-bins is first placed in polythene bags that are sealed with tape [113, ¶13]. The resultant pucks (compacted drums) are grouted into Half-Height International Standard Organisation (HHISO)-type containers for consignment to D3100.
- **Bulk[13] LLW.** Bulk solid waste items, not suitable for compaction, are loaded into HHISO containers at a suitable Dounreay site facility or, if they are too

13 Confusion has previously arisen when discussing bulk waste as to whether the waste in question is to be sentenced in a HHISO or non-containerised. To ensure as much clarity as possible, the term bulk waste is avoided wherever possible; reference is instead made to non-

large and are not suitable for size reduction, bulk items may be sentenced as non-containerised waste items directly to D3100. For consignment to D3100, HHISOs containing non-compactable LLW are filled with conditioning grout. Non-containerised LLW items sentenced directly will be grouted *in situ* in the D3100 vaults; no such items have been consigned to date.

- **Mixed LLW.** HHISO containers holding a grouted mixture of compactable and non-compactable LLW.
- **Demolition LLW.** Decommissioning and demolition waste meeting the above definition of Demolition LLW is consigned as unconditioned material for disposal in dedicated D3100 vaults. The material is generally held in 1 te polypropylene bags to ease handling arrangements.

79 However, while the term "waste package" may be used in other references for Dounreay waste on a variety of scales, at present there are effectively three types of waste package or packaged waste discussed in this ESC for disposal in D3100 – containers (generally HHISOs) of LLW, non-containerised LLW items, and Demolition LLW.

80 Further categorisation of the wastes on the basis of characteristics relevant to D3100 performance is achieved informally by the D3100 Load Management Plan that applies best practice to try to achieve an even spread of properties and separation of waste-types that might have deleterious interactions (e.g. gas generation and high ^{14}C content).

81 All waste characteristics are detailed in Project Specific Waste Plans (PSWPs) [114]. PSWPs are endorsed by DSRL Waste Operations and all waste must be packed and characterised as defined in the PSWP, its underpinning assessments and DSRL procedures. Only waste deemed to be appropriate for acceptance at D3100 by both Dounreay Waste Operations and the D3100 Compliance team is permitted for disposal. As described later in this section, conditions and procedures are applied to ensure that the wastes accepted for disposal in D3100 comply with the requirements of this ESC and the EASR 18 Authorised WAC for the facilities. The PSWPs for the wastes are a key input to demonstrating compliance of consignments from the licensed site with the Authorised WAC for D3100.

4.2 Waste Records

GRA 6.2.37(b)	Record: … records of waste form and characterisation; records of waste emplacements and their location in the facility ...

82 Previously DSRL maintained a central database of inventory information for the Dounreay site, known as the Dounreay Radioactive Waste Inventory (DRWI). Information from DRWI 2009 formed the basis for the waste inventory estimates used in preceding ESCs and was also used by SEPA to set radionuclide activity limits in the current D3100 Permit.

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compactable LLW, which will be disposed of in a HHISO, and non-containerised LLW, which consists of distinct items disposed of directly in the vaults.

83 Predictions for wastes yet to arise are now recorded by the Dounreay site in the Predictive Waste Inventory (PWI) spreadsheet. The Dounreay Data Management System (DMS) is a database used to make an electronic record of radioactive waste packages that have been consigned on the Dounreay site. The DMS is used to record waste consignments to D3100, as well as records documenting waste acceptance review by the D3100 Compliance team.

84 As discussed in paragraph 87, data sourced from the PWI and DMS supported the latest inventory estimate for LLW requiring disposal in D3100. See paragraphs 125 and 725 for more on waste records management for D3100.

85 EASR 18 Standard Condition B.8 [115] also requires that a WMP is prepared and maintained for D3100. In addition to inventory reports for radioactive wastes disposed of in the D3100 vaults (see Section 4.3), WMP requirements for wastes generated as a result of construction, operation and closure of the facilities are met through a number of documents for D3100, as follows:

- DSRL's strategic approach to waste management for the construction, operation and closure of D3100 was laid out in the Environmental Statement and the Environmental Statement Addendum [16, Ch.11]. A key aspect of this strategic approach is the sustainable re-use of excavated materials during backfill, closure and capping of the vaults. It was concluded in the Environmental Statement that, with the proposed controls and mitigation measures in place, the residual impacts associated with solid and liquid wastes produced during the construction, operation and closure of D3100 would be negligible.
- Operational waste management approaches are laid out in the Operational Management Plan (OMP, [116, §4]), with requirements for waste minimisation, and segregation of radioactive and non-radioactive wastes, highlighted. A supporting PSWP [117] has been developed to assist in the consignment of waste generated through routine and maintenance operations carried out within the D3100 project area. The PSWP identifies all waste streams expected from current and future operations, ensuring routes are available for any waste produced (all operational waste generated is expected to be radiologically clean).
- Various scenarios for the re-use of excavated material during construction and closure are considered in the D3100 Project Phases Interface Plan [118] and enclosed materials mass balance calculations. It is recognised that as disposal operations and backfilling progress, and in anticipation of future phases of construction, review of the material mass balance and development of a materials management plan is required.

FP.1	Maintain a Waste Management Plan (WMP) and develop a Materials Management Plan for D3100[14].

[14] Requirements for the forward programme are indicated using the "FP.x" numbering system throughout this ESC. The requirements are then summarised in Section 14.

4.3 D3100 Waste Inventory

86 Section 7 summarises Performance Assessment (PA) calculations for the D3100 disposal facilities. One key endpoint of the PA calculations is radiological dose/risk to the public, and an estimate of the radioactive waste inventory is required as an input to the calculations. The PA results presented in Section 7 are based on the latest predicted LLW inventory that may require disposal in the D3100 facilities, documented in the D3100 LLW Inventory Report 2020 [47]. The inventory report includes the inventory of waste that has already been disposed of in the D3100 disposal vaults and presents a range of potential inventory cases for wastes that may require disposal in the future. Future waste disposals include both historical wastes in storage and those predicted to arise from decommissioning of the Dounreay and Vulcan NRTE sites.

87 Data to compile the LLW Inventory Report 2020 were primarily drawn from the datasheets submitted by DSRL Waste Operations to the 2019 UK Radioactive Waste Inventory (UKRWI) [119] compilation. To prepare these datasheets, the DSRL inventory team reviewed inventory information for the Dounreay site from various sources, such as the Dounreay PWI (the database of waste expected to arise), DMS (the database of waste arisen and packaged) and facility staff. For wastes already disposed of in the D3100 facilities (from the start of operations up to 31 December 2018), the inventory data were sourced from a D3100 inventory summary [120], which in turn was sourced from disposal records stored in DMS.

88 The 2020 Inventory Report allocates solid LLW into a number of broad groups, according to the waste source and/or its current status. For LLW, there are five such groups: ‘Disposed LLW’ that has already been disposed of in D3100, ‘LLW Stock’ currently in stores on the Dounreay site awaiting disposal, ‘LLW Arising’ that is forecast to arise in the future, ‘LLW Pits’ waste planned to be retrieved from the historical LLW Pits Complex, and ‘Additional Streams’ comprising waste streams near the ILW/LLW boundary that may be disposable in D3100 if they are demonstrated to be LLW through additional characterisation. For Demolition LLW there are three groups: ‘Disposed Demolition LLW’, ‘Demolition LLW Stock’, and ‘Demolition LLW Arising’. Full definitions of these groups are given in Section 2 of the 2020 Inventory Report [47].

89 A key driver in the development of the 2020 Inventory Report was to address inventory uncertainty as much as possible, and so the inventory is presented in terms of both best and upper estimates. It is important to note that the upper estimate is not necessarily a bounding estimate; it is calculated using the waste volume and activity factors reported in the UKRWI datasheets for each waste stream. There is particular uncertainty associated with wastes predicted to arise as a result of future decommissioning because the waste will not be fully characterised until it is generated, and management plans and strategies may change, meaning that some waste streams may not be consigned to D3100 and some new streams could be added. These represent unknowns that cannot be accounted for in the inventory estimate. For the disposal of LLW it is known that the groups LLW Stock and LLW Arising will be disposed of in the D3100 LLW vault along with the already disposed of LLW. However, there is uncertainty regarding whether the retrieved LLW Pits waste and Additional Streams can or will be disposed of in D3100. Therefore, three

LLW inventory cases have been developed in the 2020 Inventory Report, as presented in Table 4.1.

90 There is considerable uncertainty associated with the volume of Demolition LLW that will require disposal. For example, it is possible that some future arising waste currently estimated to be LLW may be re-classed as Demolition LLW upon retrieval and characterisation, or Demolition LLW may be classified as radiologically Out of Scope of Regulation (OoSoR) and deemed suitable for disposal elsewhere. Equally, alternative decommissioning and site end state plans may lead to different assumptions about waste volume segregation and classification (e.g. proportions of building structures that will be recycled or OoSoR), or changes in strategy may mean significantly different waste volumes require disposal (e.g. exclusion of contaminated ground). The GRR suggests sites consider the option of on-site and *in situ* disposal for some bulk low-activity structures, as well as reuse of contaminated material during site remediation, which could also change the volume of Demolition LLW requiring disposal in D3100. It is not possible to quantify the impact of these changes, but they could be a few percent or they could impact the total number of vaults required. Given that the impact of such changes is not known, no alternative inventory cases are considered - only a single Demolition LLW inventory case is presented in the 2020 Inventory Report, comprising Disposed Demolition LLW, Demolition LLW Stock and Demolition LLW Arising.

Table 4.1: LLW inventory cases considered in the 2020 LLW Inventory Report [47].

Inventory Case	A	B	C
Waste Groups	Disposed LLW	Disposed LLW	Disposed LLW
	LLW Stock	LLW Stock	LLW Stock
	LLW Arising	LLW Arising	LLW Arising
		LLW Pits	LLW Pits
			Additional Streams

91 As discussed above and in paragraphs 13 and 64, proposed amendments to the legislative framework that applies to nuclear sites and ongoing review and optimisation of the Dounreay site end state, could significantly impact the volumes and timings of decommissioning wastes requiring disposal in D3100. This is a key uncertainty in the inventory estimate for D3100 and requires dialogue with the Dounreay site end state team to ensure that management of D3100 and planning for future phases of vault construction are consistent with the latest Dounreay site plans.

FP.2 Maintain dialogue with the Dounreay site end state team, and review the developing Dounreay site Waste Management Plan, to assess the impact of future changes in the site decommissioning and remediation strategy on the wastes requiring disposal in D3100 and the potential for cumulative impacts on receptors.

4.3.1 Waste volumes and masses

92 Estimated packaged waste volumes and masses are given in Table 4.2 for each LLW and Demolition LLW group. These were derived through the use of conditioning and packaging factors (the ratio between conditioned waste volume and raw waste volume, and the ratio between packaged waste volume and conditioned waste volume, respectively) to account for assumptions relating to waste treatment and packaging. The derivation of raw, conditioned and packaged waste volumes and masses, and assumptions regarding conditioning and packaging factors, are documented in Section 4 of the 2020 Inventory Report [47].

Table 4.2: Estimated packaged waste volumes and masses for waste potentially requiring disposal in the D3100 LLW and Demolition LLW vaults [47, Tab.4.1 and Tab.4.2].

Waste Category	Packaged waste volume (m^3)		Packaged waste mass (te)	
	Best estimate	Upper estimate	Best estimate	Upper estimate
LLW				
Disposed LLW	4,017	4,017	6,213	6,213
LLW Stock	13,009	13,271	22,581	23,084
LLW Arising	25,672	31,858	33,387	41,536
LLW Pits	71,936	86,323	104,251	125,105
Additional streams	478	516	1,228	1,302
Sub-total	**115,112**	**135,984**	**167,660**	**197,240**
***No. equivalent HHISOs*ᵻ**	***5,921***	***6,993***		
Demolition LLW				
Disposed Demolition LLW	965	965	1,578	1,578
Demolition LLW Stock	2,170	2,214	2,276	2,321
Demolition LLW Arising	30,271	36,325	27,193	32,631
Sub-total	**33,406**	**39,504**	**31,047**	**36,531**
***No. equivalent HHISOs*ᵻ**	***1,716***	***2,208***		
Total	**148,519**	**175,488**	**198,707**	**233,771**
***No. equivalent HHISOs*ᵻ**	***7,637***	***9,021***		

ᵻ The number of equivalent HHISOs is illustrative and assumes no mixing of waste streams within HHISOs. Demolition LLW will not be packaged in HHISOs but in bags (with a different packing density) and not all LLW will be packaged in HHISOs. However, the number of equivalent HHISOs is a convenient unit for consideration of the number of vaults required.

4.3.2 Radioactive waste inventory

93 Radionuclide activity data are provided for each waste stream in the UKRWI datasheets in terms of an activity concentration in TBq m^{-3} (1×10^{12} Bq m^{-3}) for each radionuclide. Therefore, the total activity for each radionuclide in each waste stream has been derived by multiplying the activity concentration by the raw waste stream volume. The total radionuclide inventory for solid LLW Cases A, B and C, and Demolition LLW is presented in Table 4.3 for a date of 1 January 2020.

94 The 2019 UKRWI datasheets report data for 114 radionuclides, but not all of these are present in Dounreay LLW and Demolition LLW, and others are only present in

very small amounts. Two radionuclides (^{244}Pu and ^{247}Cm) were added to the UKRWI list in the 2020 Inventory Report in order to properly account for longer-lived radionuclides in the actinide decay chains, which brought the total number of reported radionuclides in the inventory to 116.

95 Figure 4.1 presents a chart of the 33 radionuclides in the best estimate inventory forming at least 0.01% of the total activity at 1 January 2020. Figure 4.2 presents the same plot for the 36 radionuclides in the upper estimate inventory forming at least 0.01% of the total activity at 1 January 2020. The plots use a logarithmic scale so the contributions of other radionuclides can be more easily discerned, but the total activity is in fact dominated by a few radionuclides, primarily ^{137}Cs, ^{241}Pu, ^{90}Sr, ^{3}H, ^{55}Fe and ^{60}Co. All six of these radionuclides are relatively short-lived, with the longest being ^{137}Cs with a half-life of 30.2 years. Note, however, that other than ^{137}Cs, none of these radionuclides contribute significantly to calculated post-closure performance. The focus of future inventory development on the radionuclides most significant to calculated performance is discussed in Section 4.3.6.

Table 4.3: Total radionuclide best and upper estimate inventories at 1 January 2020 for LLW inventory Cases A, B and C, and Demolition LLW.

Nuclide	Half-life (y)	Activity (Bq) at 01/01/2020									
		Case A		Case B		Case C		Demolition		Total (Case C + Demolition)	
		(Stored + Disposed + Arisings)		(Stored + Disposed + Arisings + Pits)		(Stored + Disposed + Arisings + Pits + Additional waste streams)		(Stored + Disposed + Arisings)			
		Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate
^{3}H	1.23E+01	1.91E+12	1.10E+13	1.91E+12	1.10E+13	3.41E+12	1.63E+13	1.53E+09	1.84E+10	3.41E+12	1.64E+13
^{10}Be	1.51E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.12E+07	1.84E+08	0.00E+00	0.00E+00	5.12E+07	1.84E+08
^{14}C	5.70E+03	1.47E+11	3.27E+12	1.47E+11	3.27E+12	2.10E+11	3.49E+12	1.92E+08	2.30E+09	2.11E+11	3.50E+12
^{22}Na	2.60E+00	1.16E+09	7.54E+09	1.16E+09	7.54E+09	1.17E+09	7.60E+09	0.00E+00	0.00E+00	1.17E+09	7.60E+09
^{26}Al	7.17E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{36}Cl	3.01E+05	7.90E+04	2.37E+05	7.90E+04	2.37E+05	2.02E+08	7.27E+08	0.00E+00	0.00E+00	2.02E+08	7.27E+08
^{39}Ar	2.69E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.65E+08	2.39E+09	0.00E+00	0.00E+00	6.65E+08	2.39E+09
^{42}Ar	3.29E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.92E+02	6.93E+02	0.00E+00	0.00E+00	1.92E+02	6.93E+02
^{40}K	1.25E+09	1.75E+04	5.29E+04	1.75E+04	5.29E+04	2.08E+09	7.47E+09	0.00E+00	0.00E+00	2.08E+09	7.47E+09
^{41}Ca	1.02E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.23E+09	4.43E+09	0.00E+00	0.00E+00	1.23E+09	4.43E+09
^{53}Mn	3.70E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.38E-02	1.94E-01	0.00E+00	0.00E+00	5.38E-02	1.94E-01
^{54}Mn	8.55E-01	1.47E+09	4.64E+10	1.47E+09	4.64E+10	1.47E+09	4.64E+10	5.93E+04	7.12E+05	1.47E+09	4.64E+10
^{55}Fe	2.74E+00	1.48E+12	4.65E+13	1.48E+12	4.65E+13	1.48E+12	4.65E+13	1.93E+03	2.31E+04	1.48E+12	4.65E+13
^{60}Co	5.27E+00	1.46E+12	4.24E+13	1.46E+12	4.24E+13	1.53E+12	4.26E+13	2.93E+09	3.37E+10	1.53E+12	4.27E+13
^{59}Ni	1.01E+05	3.70E+03	1.12E+04	1.48E+09	5.33E+09	2.02E+09	7.26E+09	1.02E+00	1.23E+01	2.02E+09	7.26E+09
^{63}Ni	1.00E+02	2.53E+11	7.90E+12	3.57E+11	8.27E+12	4.08E+11	8.46E+12	1.29E+08	1.54E+09	4.08E+11	8.46E+12
^{65}Zn	6.68E-01	3.76E+03	1.13E+04	3.76E+03	1.13E+04	3.76E+03	1.13E+04	7.92E+00	9.51E+01	3.77E+03	1.14E+04
^{79}Se	2.95E+05	0.00E+00	0.00E+00	2.85E+07	1.03E+08	3.03E+07	1.09E+08	0.00E+00	0.00E+00	3.03E+07	1.09E+08
^{81}Kr	2.29E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.01E+08	3.63E+08	0.00E+00	0.00E+00	1.01E+08	3.63E+08
^{85}Kr	1.08E+01	3.55E+03	1.09E+04	3.55E+03	1.09E+04	2.15E+10	7.76E+10	1.09E+00	1.31E+01	2.15E+10	7.76E+10
^{87}Rb	4.92E+10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.84E+07	6.63E+07	0.00E+00	0.00E+00	1.84E+07	6.63E+07
^{90}Sr	2.88E+01	5.82E+11	6.96E+12	2.66E+12	1.44E+13	2.66E+12	1.45E+13	3.08E+11	3.68E+12	2.97E+12	1.81E+13
^{93}Zr	1.53E+06	0.00E+00	0.00E+00	1.87E+08	6.73E+08	1.87E+08	6.74E+08	0.00E+00	0.00E+00	1.87E+08	6.74E+08
^{91}Nb	6.80E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.98E+02	3.23E+03	0.00E+00	0.00E+00	8.98E+02	3.23E+03
^{92}Nb	3.47E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.24E+00	4.46E+00	0.00E+00	0.00E+00	1.24E+00	4.46E+00
^{93m}Nb	1.61E+01	1.35E+10	1.51E+11	1.36E+10	1.51E+11	1.63E+10	1.61E+11	3.22E+08	3.87E+09	1.67E+10	1.65E+11
^{94}Nb	2.03E+04	2.65E+07	1.05E+08	4.77E+08	1.73E+09	1.34E+09	4.85E+09	7.60E+05	9.13E+06	1.35E+09	4.86E+09
^{93}Mo	4.00E+03	1.36E+10	1.51E+11	1.36E+10	1.51E+11	1.36E+10	1.52E+11	3.23E+08	3.88E+09	1.39E+10	1.55E+11
^{97}Tc	2.60E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.60E+05	5.75E+05	0.00E+00	0.00E+00	1.60E+05	5.75E+05
^{99}Tc	2.11E+05	1.23E+08	1.35E+09	1.35E+09	5.77E+09	1.35E+09	5.78E+09	2.75E+06	3.30E+07	1.36E+09	5.81E+09
^{106}Ru	1.02E+00	4.10E+07	2.57E+08	4.10E+07	2.57E+08	4.10E+07	2.57E+08	2.32E+07	2.78E+08	6.42E+07	5.36E+08
^{107}Pd	6.50E+06	0.00E+00	0.00E+00	1.73E+07	6.23E+07	1.73E+07	6.24E+07	0.00E+00	0.00E+00	1.73E+07	6.24E+07
^{108m}Ag	4.18E+02	1.20E+07	1.07E+08	1.20E+07	1.07E+08	5.58E+07	2.65E+08	3.06E+06	3.67E+07	5.88E+07	3.01E+08
^{110m}Ag	6.84E-01	1.80E+09	5.69E+10	1.80E+09	5.69E+10	1.80E+09	5.69E+10	0.00E+00	0.00E+00	1.80E+09	5.69E+10
^{109}Cd	1.26E+00	8.33E+07	8.41E+08	8.33E+07	8.41E+08	8.33E+07	8.41E+08	9.34E+06	1.12E+08	9.27E+07	9.53E+08
^{113m}Cd	1.41E+01	4.44E+01	1.36E+02	4.44E+01	1.36E+02	1.54E+08	5.54E+08	1.26E-02	1.51E-01	1.54E+08	5.54E+08
^{119m}Sn	8.02E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{121m}Sn	4.39E+01	1.09E+08	1.22E+09	1.09E+08	1.22E+09	1.18E+08	1.25E+09	2.72E+06	3.26E+07	1.21E+08	1.28E+09
^{123}Sn	3.54E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{126}Sn	2.30E+05	0.00E+00	0.00E+00	2.10E+08	7.56E+08	2.10E+08	7.56E+08	0.00E+00	0.00E+00	2.10E+08	7.56E+08
^{125}Sb	2.76E+00	1.71E+10	4.78E+11	1.71E+10	4.78E+11	1.71E+10	4.78E+11	5.41E+08	6.49E+09	1.76E+10	4.84E+11
^{126}Sb	3.38E-02	0.00E+00	0.00E+00	2.10E+08	7.56E+08	2.10E+08	7.56E+08	0.00E+00	0.00E+00	2.10E+08	7.56E+08

Nuclide	Half-life (y)	Activity (Bq) at 01/01/2020									
		Case A (Stored + Disposed + Arisings)		Case B (Stored + Disposed + Arisings + Pits)		Case C (Stored + Disposed + Arisings + Pits + Additional waste streams)		Demolition (Stored + Disposed + Arisings)		Total (Case C + Demolition)	
		Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate
^{125m}Te	1.57E-01	4.00E+09	1.12E+11	4.00E+09	1.12E+11	4.00E+09	1.12E+11	1.27E+08	1.52E+09	4.13E+09	1.14E+11
^{127m}Te	2.98E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{129}I	1.57E+07	0.00E+00	0.00E+00	2.31E+06	8.31E+06	2.32E+06	8.34E+06	0.00E+00	0.00E+00	2.32E+06	8.34E+06
^{134}Cs	2.06E+00	8.10E+09	2.24E+11	8.10E+09	2.24E+11	8.16E+09	2.24E+11	1.91E+08	2.29E+09	8.35E+09	2.26E+11
^{135}Cs	2.30E+06	0.00E+00	0.00E+00	1.23E+08	4.42E+08	1.23E+08	4.42E+08	0.00E+00	0.00E+00	1.23E+08	4.42E+08
^{137}Cs	3.02E+01	1.41E+12	1.50E+13	4.05E+12	2.46E+13	3.22E+13	1.26E+14	3.79E+11	4.50E+12	3.26E+13	1.30E+14
^{133}Ba	1.05E+01	1.15E+08	8.26E+08	1.15E+08	8.26E+08	1.43E+09	5.56E+09	1.94E+07	2.33E+08	1.45E+09	5.79E+09
^{137}La	6.00E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.20E+06	1.15E+07	0.00E+00	0.00E+00	3.20E+06	1.15E+07
^{138}La	1.02E+11	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.88E+02	1.04E+03	0.00E+00	0.00E+00	2.88E+02	1.04E+03
^{144}Ce	7.80E-01	8.32E+09	2.62E+11	8.32E+09	2.62E+11	8.32E+09	2.62E+11	3.41E+02	4.09E+03	8.32E+09	2.62E+11
^{145}Pm	1.77E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.75E+07	6.30E+07	0.00E+00	0.00E+00	1.75E+07	6.30E+07
^{147}Pm	2.62E+00	8.04E+10	9.13E+11	8.05E+10	9.13E+11	8.05E+10	9.13E+11	3.19E+09	3.81E+10	8.37E+10	9.51E+11
^{147}Sm	1.06E+11	4.43E-01	4.98E+00	6.27E-01	5.64E+00	9.90E+02	3.57E+03	1.74E-02	2.07E-01	9.90E+02	3.57E+03
^{151}Sm	9.00E+01	7.82E+09	5.46E+10	1.93E+11	7.23E+11	1.98E+11	7.40E+11	5.94E+08	7.12E+09	1.99E+11	7.47E+11
^{152}Eu	1.35E+01	2.89E+10	2.72E+11	3.39E+11	1.39E+12	3.90E+11	1.57E+12	1.86E+09	2.20E+10	3.91E+11	1.59E+12
^{154}Eu	8.59E+00	5.47E+10	1.18E+12	6.50E+10	1.22E+12	7.75E+10	1.26E+12	1.75E+09	2.07E+10	7.92E+10	1.28E+12
^{155}Eu	4.76E+00	2.43E+10	6.59E+11	2.54E+10	6.63E+11	2.56E+10	6.63E+11	4.99E+08	5.99E+09	2.61E+10	6.69E+11
^{153}Gd	6.58E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{163}Ho	4.57E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.90E+06	1.40E+07	0.00E+00	0.00E+00	3.90E+06	1.40E+07
^{166m}Ho	1.20E+03	2.38E+02	7.28E+02	2.38E+02	7.28E+02	6.36E+08	2.29E+09	4.99E-02	5.99E-01	6.36E+08	2.29E+09
^{170}Tm	3.52E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{171}Tm	1.92E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.67E+05	9.62E+05	0.00E+00	0.00E+00	2.67E+05	9.62E+05
^{174}Lu	3.31E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.71E+02	3.14E+03	0.00E+00	0.00E+00	8.71E+02	3.14E+03
^{176}Lu	3.85E+10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.74E+02	1.71E+03	0.00E+00	0.00E+00	4.74E+02	1.71E+03
^{178n}Hf	3.10E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.78E+04	1.36E+05	0.00E+00	0.00E+00	3.78E+04	1.36E+05
^{182}Hf	9.00E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.02E+01	7.27E+01	0.00E+00	0.00E+00	2.02E+01	7.27E+01
^{193}Pt	5.00E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.74E+09	1.71E+10	0.00E+00	0.00E+00	4.74E+09	1.71E+10
^{204}Tl	3.78E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.41E+10	3.03E+11	0.00E+00	0.00E+00	8.41E+10	3.03E+11
^{205}Pb	1.53E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.05E+02	2.90E+03	0.00E+00	0.00E+00	8.05E+02	2.90E+03
^{210}Pb	2.22E+01	2.30E+09	7.03E+09	7.09E+09	2.43E+10	1.11E+10	6.51E+10	2.71E+03	3.25E+04	1.11E+10	6.51E+10
^{208}Bi	3.68E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.58E+01	9.29E+01	0.00E+00	0.00E+00	2.58E+01	9.29E+01
^{210m}Bi	3.04E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.47E+02	3.05E+03	0.00E+00	0.00E+00	8.47E+02	3.05E+03
^{210}Po	3.79E-01	4.96E+09	1.52E+10	9.66E+09	3.21E+10	1.35E+10	7.11E+10	1.57E+04	1.88E+05	1.35E+10	7.11E+10
^{223}Ra	3.13E-02	5.85E+02	2.81E+03	1.43E+05	5.17E+05	1.21E+06	2.44E+06	3.67E+00	4.33E+01	1.21E+06	2.44E+06
^{225}Ra	4.08E-02	2.78E-01	1.37E+00	4.50E-01	1.99E+00	1.88E+06	6.76E+06	3.26E-07	3.90E-06	1.88E+06	6.76E+06
^{226}Ra	1.60E+03	9.91E+10	3.03E+11	1.10E+11	3.42E+11	1.24E+11	4.86E+11	1.17E+05	1.40E+06	1.24E+11	4.86E+11
^{228}Ra	5.75E+00	2.64E+07	2.23E+08	3.49E+08	1.38E+09	1.64E+10	4.94E+10	2.84E+05	3.41E+06	1.64E+10	4.94E+10
^{227}Ac	2.18E+01	8.10E+02	3.91E+03	1.51E+05	5.43E+05	1.24E+06	2.49E+06	5.14E+00	6.07E+01	1.24E+06	2.49E+06
^{227}Th	5.11E-02	6.63E+02	3.19E+03	1.45E+05	5.24E+05	1.21E+06	2.45E+06	4.18E+00	4.93E+01	1.21E+06	2.45E+06
^{228}Th	1.91E+00	1.87E+08	6.77E+08	6.62E+08	2.39E+09	1.67E+10	5.04E+10	1.06E+06	1.28E+07	1.67E+10	5.04E+10
^{229}Th	7.34E+03	3.01E-01	1.49E+00	4.76E-01	2.12E+00	1.88E+06	6.77E+06	3.90E-07	4.67E-06	1.88E+06	6.77E+06
^{230}Th	7.54E+04	3.56E+06	1.37E+07	2.64E+07	9.60E+07	4.69E+07	1.27E+08	8.35E+03	9.69E+04	4.69E+07	1.27E+08
^{232}Th	1.41E+10	5.42E+07	5.08E+08	5.42E+07	5.08E+08	1.61E+10	4.85E+10	4.94E+05	5.93E+06	1.61E+10	4.85E+10
^{234}Th	6.60E-02	9.95E+08	5.02E+09	4.87E+09	1.90E+10	4.88E+09	1.90E+10	8.20E+06	6.53E+07	4.89E+09	1.91E+10
^{231}Pa	3.28E+04	6.53E+04	3.20E+05	1.53E+06	5.60E+06	3.38E+06	8.78E+06	4.32E+02	5.11E+03	3.38E+06	8.78E+06

Nuclide	Half-life (y)	Activity (Bq) at 01/01/2020									
		Case A		Case B		Case C		Demolition		Total (Case C + Demolition)	
		(Stored + Disposed + Arisings)		(Stored + Disposed + Arisings + Pits)		(Stored + Disposed + Arisings + Pits + Additional waste streams)		(Stored + Disposed + Arisings)			
		Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate
^{233}Pa	7.38E-02	5.23E+06	5.61E+07	6.43E+06	6.05E+07	6.44E+06	6.05E+07	4.82E+03	5.77E+04	6.44E+06	6.05E+07
^{232}U	6.89E+01	2.06E+08	7.24E+08	2.06E+08	7.24E+08	2.06E+08	7.24E+08	3.73E+06	4.48E+07	2.09E+08	7.69E+08
^{233}U	1.59E+05	4.25E+03	2.11E+04	4.58E+03	2.23E+04	5.61E+08	2.02E+09	1.27E-02	1.53E-01	5.61E+08	2.02E+09
^{234}U	2.46E+05	1.57E+11	8.89E+11	5.55E+11	2.32E+12	5.93E+11	2.38E+12	1.20E+09	1.40E+10	5.94E+11	2.39E+12
^{235}U	7.04E+08	3.97E+09	1.97E+10	1.51E+10	5.97E+10	1.64E+10	6.18E+10	2.71E+07	3.21E+08	1.64E+10	6.21E+10
^{236}U	2.34E+07	1.64E+10	1.04E+11	4.31E+10	2.00E+11	4.31E+10	2.00E+11	1.38E+08	1.64E+09	4.33E+10	2.02E+11
^{238}U	4.47E+09	9.95E+08	5.02E+09	4.87E+09	1.90E+10	4.88E+09	1.90E+10	8.21E+06	6.54E+07	4.89E+09	1.91E+10
^{237}Np	2.14E+06	5.24E+06	5.62E+07	6.45E+06	6.06E+07	6.45E+06	6.06E+07	4.92E+03	5.89E+04	6.46E+06	6.06E+07
^{236}Pu	2.86E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{238}Pu	8.77E+01	7.52E+10	4.69E+11	1.61E+11	7.76E+11	1.61E+11	7.76E+11	1.84E+09	2.15E+10	1.63E+11	7.98E+11
^{239}Pu	2.41E+04	7.67E+10	4.35E+11	6.96E+11	2.67E+12	7.00E+11	2.68E+12	4.49E+09	5.33E+10	7.05E+11	2.73E+12
^{240}Pu	6.56E+03	8.59E+10	3.62E+11	3.26E+11	1.23E+12	3.26E+11	1.23E+12	6.55E+08	7.25E+09	3.27E+11	1.23E+12
^{241}Pu	1.44E+01	1.07E+12	1.04E+13	3.19E+12	1.80E+13	3.19E+12	1.80E+13	1.17E+10	1.37E+11	3.21E+12	1.82E+13
^{242}Pu	3.75E+05	5.79E+07	1.82E+08	1.51E+08	5.16E+08	1.51E+08	5.16E+08	9.22E+05	1.11E+07	1.52E+08	5.27E+08
^{244}Pu	8.00E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{241}Am	4.32E+02	1.18E+11	5.57E+11	3.89E+11	1.53E+12	3.89E+11	1.53E+12	2.88E+09	3.39E+10	3.92E+11	1.57E+12
^{242m}Am	1.41E+02	3.97E+08	1.73E+09	3.30E+09	1.22E+10	3.30E+09	1.22E+10	2.33E+07	2.80E+08	3.32E+09	1.24E+10
^{243}Am	7.37E+03	4.87E+06	3.19E+07	4.87E+06	3.19E+07	4.87E+06	3.19E+07	6.29E+05	7.54E+06	5.50E+06	3.94E+07
^{242}Cm	4.46E-01	4.10E+08	1.92E+09	3.16E+09	1.18E+10	3.16E+09	1.18E+10	2.46E+07	2.95E+08	3.19E+09	1.21E+10
^{243}Cm	2.91E+01	4.47E+07	2.55E+08	4.47E+07	2.55E+08	4.47E+07	2.55E+08	4.50E+06	5.40E+07	4.92E+07	3.09E+08
^{244}Cm	1.81E+01	1.62E+09	8.61E+09	1.62E+09	8.61E+09	1.62E+09	8.61E+09	1.23E+09	1.48E+10	2.85E+09	2.34E+10
^{245}Cm	8.50E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{246}Cm	4.76E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{247}Cm	1.56E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{248}Cm	3.48E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{249}Cf	3.51E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{250}Cf	1.31E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{251}Cf	9.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
^{252}Cf	2.65E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total α		**6.41E+11**	**3.17E+12**	**2.32E+12**	**9.20E+12**	**2.41E+12**	**9.56E+12**	**1.25E+10**	**1.47E+11**	**2.42E+12**	**9.70E+12**
Total non-α		**8.58E+12**	**1.48E+14**	**1.61E+13**	**1.75E+14**	**4.61E+13**	**2.83E+14**	**7.13E+11**	**8.49E+12**	**4.68E+13**	**2.92E+14**
Total		**9.22E+12**	**1.51E+14**	**1.84E+13**	**1.84E+14**	**4.85E+13**	**2.93E+14**	**7.26E+11**	**8.63E+12**	**4.92E+13**	**3.01E+14**

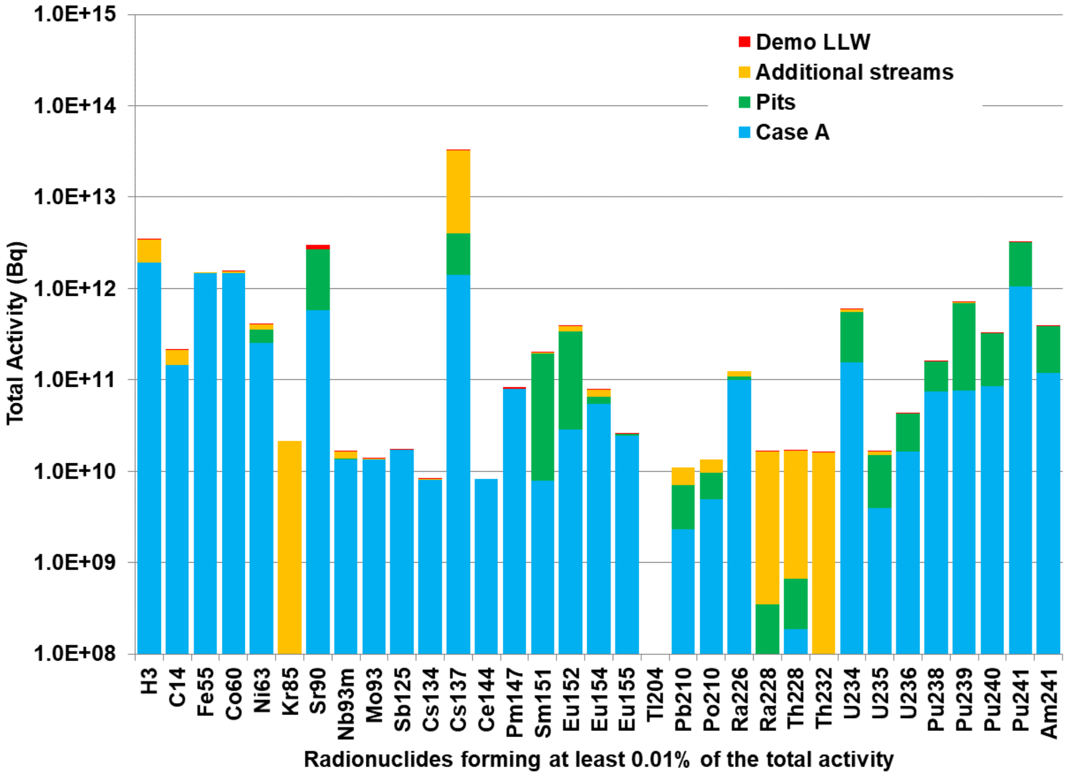

Figure 4.1: The 33 nuclides comprising at least 0.01% of the total best estimate inventory by activity in Bq at 1 January 2020 (logarithmic scale).

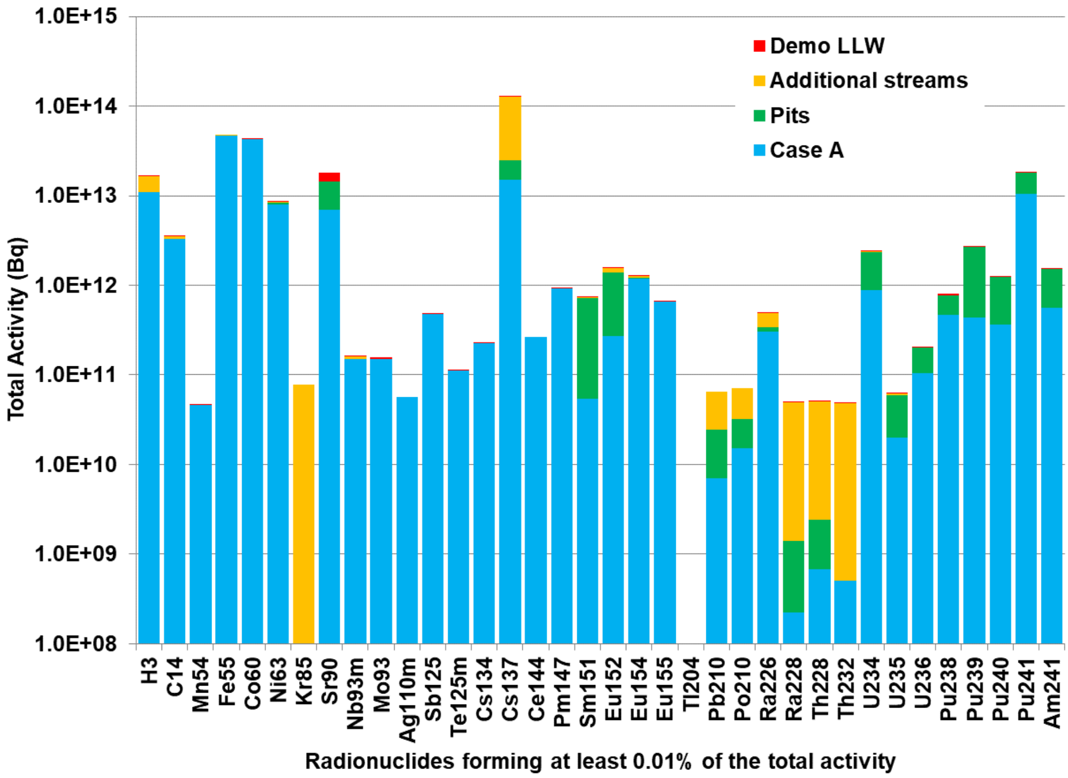

Figure 4.2: The 36 nuclides comprising at least 0.01% of the total upper estimate inventory by activity in Bq at 1 January 2020 (logarithmic scale).

4.3.3 Materials inventory

96 Table 4.4 presents the breakdown of the raw waste inventory by principal material category for the LLW Case A, B and C, and Demolition LLW best and upper inventory estimates. These have been derived from the 2019 UKRWI datasheet submissions, which provide material compositions by weight percentage for each waste stream, and the total mass for each raw waste stream. The principal material categories are defined as those forming at least 1 wt% of the materials inventory.

97 In addition to the waste materials presented in Table 4.4, significant masses of clean grout, steel and sand are included in the waste packages consigned to D3100 and in the D3100 vaults [47, §6.2]:

- The mass of grout to infill all the LLW HHISOs is 87,394 te and 103,217 te for best and upper estimates respectively. Additional grout will also be used for infilling the spaces between packages in the LLW vaults.
- The mass of packaging steel for LLW HHISOs is 20,724 te and 24,476 te for best and upper estimates, respectively.
- The mass of sand assumed to fill and cover Demolition LLW bags is 9,683 te and 11,380 te for best and upper estimates, respectively.
- The mass of the polypropylene bags used for Demolition LLW is estimated to be 121 te (best estimate) and 143 te (upper estimate).

98 The properties and quantities of the materials estimated to be present in the inventory have been considered and addressed as appropriate in the performance assessment calculations (see Section 7). For example:

- Cementitious materials are considered in defining the alkaline environment and its duration, and in the sorption characteristics of the near-field.
- Corrosion of iron and steel is considered in defining the redox environment and in modelling of gas generation.
- Degradation of cellulose and other organic materials is considered in assessment of gas generation.
- The inventory of hazardous materials, such as lead and asbestos, is considered in the assessment of NoRaH discussed in the following sub-section.

Table 4.4: Breakdown of total raw waste inventory by principal material category (those forming at least 1 wt%) for best and upper estimate inventories [47, Tab.6.1]. The total raw waste mass for material categories each comprising less than 1 wt% forms about an additional 500 te.

Principal material group	Raw waste material mass (te)							
	Case A		Case B		Case C		Demolition	
	Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate
Stainless steel and other ferrous metals	11,899	13,565	30,344	35,699	30,421	35,780	3,517	4,132
Lead	791	861	2,635	3,074	2,635	3,074	74	87
All other metals	1,031	1,092	1,569	1,739	1,570	1,739	12	14
Cellulosics	964	1,075	967	1,080	967	1,080	1	1
Plastics	1,083	1,225	2,374	2,774	2,374	2,774	6	6
Rubber	347	364	1,307	1,515	1,307	1,515	24	28
Soil	31	31	34	36	34	36	8,807	10,514
Brick/Stone/Rubble	707	728	707	728	707	728	138	139
Cementitious material	4,715	5,136	14,601	17,000	14,959	17,364	8,264	9,687
Glass/Ceramics	100	114	3,235	3,877	3,237	3,879	-	-
Asbestos	104	123	897	1,075	897	1,075	-	-
Other non-metals	376	448	391	465	1,028	1,152	410	412
Total	**22,148**	**24,763**	**59,064**	**69,062**	**60,136**	**70,196**	**21,253**	**25,020**

4.3.4 Hazardous materials inventory

99 In addition to radioactivity, LLW may contain materials that potentially represent a non-radiological hazard (NoRaH). The UKRWI records a wide range of materials by weight percentage, including potentially hazardous non-radiological contaminants. However, there is uncertainty associated with this materials inventory as there is incomplete coverage in the UKRWI datasheets, with little or no information available for some waste streams, and the material content often simply recorded as “P” (present), “NE” (not estimated) or “TR” (trace). Where quantities of materials/chemicals have been identified as being potentially present in trace amounts for a particular waste stream, they have been assumed to contribute 0.01% of the waste stream by weight; this is deemed to be cautious as it is considered that this assumption will lead to an overestimate of the amounts of trace contaminants [47, §3.5 and §7.1]. Table 4.5 presents the best and upper total estimates for all materials reported in the 2020 inventory, combining the estimates for both LLW and Demolition LLW. The majority of the non-radiological hazards are contained in the LLW; the minor contribution of Demolition LLW to the totals is discussed further below.

Table 4.5: Total calculated best and upper estimate masses of all materials reported in the 2019 UKRWI datasheets for the LLW and Demolition LLW streams considered in the 2020 inventory, including potentially hazardous non-radiological contaminants.

Materials	Raw waste total mass fraction (%wt)		Raw waste material mass (te)	
	Best estimate	Upper estimate	Best estimate	Upper estimate
Stainless steel	13.339	13.982	10,856.6	13,313.4
Other ferrous metals	28.359	27.935	23,081.6	26,598.5
Iron	0.048	0.049	39.0	46.8
Aluminium	0.144	0.138	117.6	131.2
Beryllium	0.005	0.005	3.7	4.4
Copper	0.756	0.750	615.5	714.2
Lead	3.328	3.320	2,709.0	3,161.3
Magnox /Magnesium	0.001	0.001	0.9	1.0
Titanium	<0.001	<0.001	0.3	0.4
Uranium[15]	0.000	0.000	0.0	0.0
Zinc	0.003	0.003	2.4	2.8
Zirconium /Zircaloy	0.001	0.001	0.9	1.0
Other metals	0.985	0.894	801.6	851.5
Total cellulosics	1.190	1.136	968.5	1,081.2
Halogenated plastics	0.964	0.954	784.7	907.9
Total non-halogenated plastics	1.960	1.966	1,594.9	1,872.1
Total rubber	1.634	1.620	1,330.1	1,542.5
Hydrocarbons	0.062	0.063	50.6	60.5
Other organics	0.090	0.092	73.3	87.9
Inorganic sludges and flocs	0.053	0.051	42.9	48.9
Soil	10.863	11.079	8,841.4	10,549.3
Brick/Stone/Rubble	1.039	0.910	845.2	866.9
Cementitious material	28.533	28.410	23,222.7	27,051.0
Sand	0.490	0.419	398.9	398.9
Glass/Ceramics	3.978	4.074	3,237.4	3,879.1
Graphite	0.344	0.339	279.9	322.7
Asbestos - total	1.103	1.129	897.3	1,075.0
Free aqueous liquids	0.027	0.023	21.7	22.3
Fluoride	<0.001	<0.001	0.3	0.4
Chloride	<0.001	<0.001	0.3	0.4
Cyanide	<0.001	<0.001	0.3	0.4

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15 Note that the uranium masses here are given as zero because no weight percentages of uranium are reported in the material compositions given in the UKRWI datasheets. This is the case even for streams reporting activity associated with uranium isotopes and so within the 2020 Inventory Report, the mass of uranium has been calculated from the reported activity [47, §7.2] (see also Section 4.3.5).

Materials	Raw waste total mass fraction (%wt)		Raw waste material mass (te)	
	Best estimate	Upper estimate	Best estimate	Upper estimate
Carbonate	<0.001	<0.001	0.4	0.4
Nitrate	0.027	0.025	22.3	23.4
Nitrite	<0.001	<0.001	0.3	0.4
Phosphate	0.006	0.006	4.7	5.5
Sulphate	0.393	0.343	320.0	326.4
Sulphide	<0.001	<0.001	0.3	0.4
Cadmium	0.005	0.005	3.8	4.6
Electronic and Electrical Equipment (EEE)	0.262	0.269	213.4	255.9
Total complexing agents	0.005	0.005	4.3	5.1
Total	**100.000**	**100.000**	**81,389.3**	**95,215.9**

Note that the UKRWI also tracks the following materials, but they were not reported to be present in the datasheets prepared by DSRL: cobalt, nickel, organic and inorganic ion exchange materials, desiccants/catalysts, free non-aqueous liquids, powder/ash, iodide, combustible metals, low flash point liquids, explosive materials, phosphorus, hydrides, biological etc. materials, biodegradable materials, corrosive materials, pyrophoric materials, generating toxic gases, reacting with water, active particles, soluble solids as bulk chemical compounds, acrylamide, benzene, chlorinated solvents, formaldehyde, organometallics, phenol, styrene, tri-butyl phosphate, other organophosphates, vinyl chloride, arsenic, barium, boron, caesium, selenium, chromium, molybdenum, thallium, tin, vanadium, mercury compounds, other H/non-H pollutants.

100 Table 4.5 indicates that the inventories of NoRaH in LLW, other than lead, copper and asbestos, are very low, making up less than 0.5% by weight of the raw wastes. The majority of the lead, copper and asbestos is expected to arise from the LLW Pits wastes. Raw LLW in Case A is estimated to contain 791 te lead, 245 te copper and 104 te asbestos (best estimate). Raw LLW from the LLW Pits wastes (the difference between Case A and B) is estimated to comprise 1,845 te lead, 369 te copper and 793 te asbestos (best estimate).

101 Lead, which has been used extensively as a shielding material for dose reduction purposes, is mainly in the form of metal bricks and sheeting, and will be largely immobile. Similarly, copper is mostly in the form of copper piping and copper wires, and will generally not be readily leachable. The quantity of lead and copper that is finally disposed of as waste may be smaller than indicated in Table 4.5 as some proportions of this metal may be suitable for recycling. Asbestos will be immobilised during conditioning with cement grout.

102 The Demolition LLW streams consist of soil and demolition materials such as concrete and brickwork. In general, unless contaminated with a hazardous material, Demolition LLW does not qualify as hazardous waste. However, contaminated soils might contain traces of hazardous materials, mainly metals or hydrocarbons. Demolition LLW is currently predicted to contain 74 te lead and 2 te copper, although no asbestos. Should it prove necessary, the incidence of any such non-radiological hazards in Demolition LLW will be controlled through the waste acceptance process, as discussed Section 4.3.7.

103 The GRA requires that the operator demonstrate that the disposal system provides adequate protection against non-radiological hazards, which is discussed in Section 7.10. However, it is noted here that, compared to the amount of hazardous wastes disposed of in dedicated hazardous waste landfills, the quantity of NoRaH waste predicted to be disposed of in D3100 is small; D3100 is primarily a disposal facility for radioactive wastes that may also have some associated NoRaH components. Whitemoss Landfill site in Lancashire, for example, is permitted to dispose of 150,000 te per year of hazardous waste in its facilities [121, Tab.S1.5].

4.3.5 Inventory of materials with implications for criticality safety

104 The best and upper estimate inventories for masses of fissile and fissionable nuclides are presented in Table 4.6. The LLW inventory is dominated by ^{235}U, with a best estimate of 204 kg, of which 139 kg (68%) is estimated to be present in the waste that may be retrieved from the LLW Pits. The LLW ^{235}U upper estimate is 771 kg, which continues to be dominated by the LLW Pits estimate (65%, or 499 kg ^{235}U), with which there is considerable uncertainty. The best estimate for the ^{239}Pu LLW inventory is substantially smaller at only 0.3 kg, rising to 1.2 kg in the upper estimate.

105 The Demolition LLW contains substantially less fissile material, with a total best estimate of 0.3 kg ^{235}U and an upper estimate of 4.0 kg ^{235}U. The ^{239}Pu content of Demolition LLW is negligible, with an upper estimate of only 0.02 kg in the entire inventory.

106 As potential neutron moderators and/or reflectors, the inventory of graphite, beryllium and polythene in the wastes has been considered in the criticality safety assessment [47, §8; 52, §4]:

- Most of the graphite arising from decommissioning of the Dounreay site is categorised as ILW. However, some small amounts of graphite are included in the LLW inventory. The best estimate inventory analysis indicates a mass of approximately 280 te, increasing to 323 te graphite in the upper estimate. The UKRWI datasheets for the LLW Pits and Demolition LLW do not record the presence of graphite.

- Beryllium is identified as being present in trace amounts in waste from the historic LLW Pits Complex. Cautiously assuming that trace is equivalent to 0.01 wt%, the Pits waste contains best and upper estimates of 3.7 te and 4.4 te of beryllium, respectively. Beryllium is identified in a number of UKRWI datasheets as being present but is not quantified, and its presence in some waste streams is identified as “not evaluated”. Beryllium is not recorded in Demolition LLW.

- The presence of polythene has been quantified for 31 waste streams, where the reported content of non-halogenated plastics has been assumed to be polythene. These waste streams encompass solid LLW, waste from the LLW Pits and Demolition LLW. The best estimate and upper estimate inventories provide total masses of polythene of 1,595 te and 1,872 te, respectively.

Table 4.6: Non-zero masses of fissionable and fissile nuclides present in the 2020 inventory estimate at 1 January 2020 [47, Tab.8.1].

Nuclide	Mass (kg)							
	Case A		Case B		Case C		Demolition LLW	
	Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate	Best estimate	Upper estimate
^{228}Th	6.16E-09	2.23E-08	2.18E-08	7.85E-08	5.49E-07	1.66E-06	3.50E-11	4.21E-10
^{231}Pa	3.73E-08	1.83E-07	8.75E-07	3.20E-06	1.93E-06	5.01E-06	2.46E-10	2.92E-09
^{232}U	2.59E-07	9.12E-07	2.59E-07	9.12E-07	2.59E-07	9.13E-07	4.70E-09	5.64E-08
^{233}U	1.19E-08	5.87E-08	1.28E-08	6.20E-08	1.56E-03	5.63E-03	3.55E-14	4.25E-13
^{234}U	6.78E-01	3.84E+00	2.40E+00	1.00E+01	2.56E+00	1.03E+01	5.18E-03	6.05E-02
^{235}U	4.96E+01	2.46E+02	1.88E+02	7.45E+02	2.04E+02	7.71E+02	3.38E-01	4.01E+00
^{236}U	6.83E+00	4.34E+01	1.80E+01	8.35E+01	1.80E+01	8.35E+01	5.76E-02	6.85E-01
^{238}U	7.99E+01	4.03E+02	3.91E+02	1.52E+03	3.92E+02	1.52E+03	6.59E-01	5.25E+00
^{237}Np	2.00E-04	2.15E-03	2.47E-04	2.32E-03	2.47E-04	2.32E-03	1.88E-07	2.25E-06
^{238}Pu	1.19E-04	7.38E-04	2.53E-04	1.22E-03	2.53E-04	1.22E-03	2.90E-06	3.39E-05
^{239}Pu	3.33E-02	1.89E-01	3.02E-01	1.16E+00	3.04E-01	1.16E+00	1.95E-03	2.31E-02
^{240}Pu	1.02E-02	4.29E-02	3.86E-02	1.45E-01	3.86E-02	1.45E-01	7.75E-05	8.59E-04
^{241}Pu	2.79E-04	2.72E-03	8.36E-04	4.72E-03	8.36E-04	4.72E-03	3.08E-06	3.59E-05
^{242}Pu	3.98E-04	1.25E-03	1.04E-03	3.55E-03	1.04E-03	3.55E-03	6.33E-06	7.60E-05
^{241}Am	9.26E-04	4.38E-03	3.06E-03	1.20E-02	3.06E-03	1.20E-02	2.27E-05	2.67E-04
^{243}Am	6.59E-07	4.31E-06	6.59E-07	4.31E-06	6.59E-07	4.31E-06	8.51E-08	1.02E-06
^{242m}Am	1.10E-06	4.80E-06	9.15E-06	3.38E-05	9.15E-06	3.38E-05	6.47E-08	7.76E-07
^{243}Cm	2.33E-08	1.33E-07	2.33E-08	1.33E-07	2.33E-08	1.33E-07	2.35E-09	2.82E-08
^{244}Cm	5.38E-07	2.87E-06	5.38E-07	2.87E-06	5.38E-07	2.87E-06	4.11E-07	4.93E-06
Total	**1.37E+02**	**6.97E+02**	**6.00E+02**	**2.36E+03**	**6.17E+02**	**2.39E+03**	**1.06E+00**	**1.00E+01**

4.3.6 Inventory development and uncertainties

107 Most wastes have yet to arise, facilities are not yet decommissioned and management plans are not fully optimised, which means that there are many uncertainties associated with the wastes, and a number of assumptions must be made in order to compile the inventory estimate. The 2020 Inventory Report presents an analysis of the changes from the previous 2009 assessment [122], on which the last issue of this ESC was based, in terms of waste volume, materials and radioactivity [47, §9.1]. However, the inventory used in ESC 2010 and its supporting assessments was adjusted from the baseline estimate presented in the 2009 inventory report, to reflect revised expectations for the LLW Pits and Demolition LLW streams [29, ¶67]. Thus, the comparison below considers the best estimate data from the 2020 Inventory Report (excluding the Additional Streams), as summarised in the previous sections, and the inventory estimate data presented in ESC 2010 Issue 2.

108 Changing from sourcing inventory information from the obsolete DRWI database (as used in ESC 2010) to using the UKRWI datasheets (see paragraphs 82 and 87) has led to a reduction in the number of individual waste streams reported from 247 to 36, as many of the original Dounreay site streams have been renamed, removed or

combined with others to produce the UKRWI waste streams. Therefore, inventory data are not discretised to the same degree as previously, and it has not been possible within the scope of this work to definitively trace back to the original waste streams from the UKRWI streams. This means that it has only been possible to compare the inventories at a high level, without identifying the changes in individual waste streams.

- Waste volume:
  - The packaged LLW volume has increased by 6% overall, primarily due to an increase of about 10% in the LLW Pits volume estimate. The estimated Demolition LLW volume has decreased by about 15%.
  - The total number of equivalent HHISOs across all wastes has increased from 7,555 (ESC 2010 Issue 2) to 7,610 (best estimate assuming no additional streams and no mixing of streams) in 2020.
- Materials:
  - There are considerable differences in the material estimates for LLW (excluding the Pits), with the stainless steel mass reduced by about 25%, the cellulosic content roughly halved, the rubber content doubled, and the rubble content halved. However, the greatest difference for this waste group is a reduction of 95% in the soil content. The LLW Pits material masses are ~10% greater than previously, but the material type proportions remain unchanged. The Demolition LLW materials also show large differences, with more than a 650% increase in the steel content, the soil and cement contents halved, and the rubble content reduced by more than 95%.
  - The hazardous material content estimated for LLW (excluding the Pits) has increased, with the estimates for the three key materials (lead, copper and asbestos) all increasing by more than 300%. The LLW Pits estimates for these materials have increased by ~10%. No quantitative estimates for the hazardous content in Demolition LLW were available previously and so the 2020 inventory estimates are new.
  - The best estimate uranium content has decreased for LLW (excluding the LLW Pits) and Demolition LLW by about 10%. The previous LLW Pits value was regarded to be an underestimate and has now increased significantly, from 12 kg to 462 kg uranium.
- Radioactivity:
  - The total LLW activity, including the LLW Pits, has increased from 1.34×10^{13} Bq to 1.84×10^{13} Bq[16], with the alpha component doubling. The total Demolition LLW activity has stayed approximately constant with

16 This neglects decay and ingrowth occurring in the 11 years between the two inventory estimates (2009 and 2020). Decaying the 2009 inventory to 2020 gives a total of 9.94×10^{12} Bq for LLW and 7.26×10^{11} Bq for Demolition LLW.

a slight decrease from 7.39×10^{11} Bq to 7.26×10^{11} Bq, with the total alpha activity component reducing to 20% of the 2009 inventory.

- Considering the total LLW inventory, in the previous estimate the radionuclides ^{137}Cs, ^{90}Sr, ^{3}H and ^{241}Pu (in decreasing order) were the four greatest contributors to the total activity. However, in 2020, the greatest contributors are ^{137}Cs, ^{241}Pu, ^{90}Sr, and ^{55}Fe (in decreasing order). The large increase in ^{55}Fe (and ^{60}Co) activities arises from Vulcan NRTE waste stream estimates.
- For the Demolition LLW inventory, ^{137}Cs, ^{241}Pu and ^{90}Sr were the greatest contributors to the total activity, but ^{3}H now gives a larger contribution than ^{241}Pu.

109 The 2020 upper inventory estimate predicts that the number of waste packages requiring disposal could slightly exceed the permitted volume (six vaults / 175,000 m^3) in the 2008 planning application [16], based on the estimated number of equivalent HHISOs [47, §4]. However, these estimates are not certain. Quantitatively, uncertainty has been addressed through application of the volume and activity uncertainty uplift factors reported in the UKRWI datasheets and by consideration of several inventory cases as described above. However, there are uncertainties that cannot be quantitatively addressed and which have the potential to be significant. These include:

- potential additional wastes which could be identified for disposal as LLW in D3100 in the future that are not currently included in the inventory;
- estimation of waste volumes and packing efficiencies;
- time of arising of waste packages;
- representativeness of sampling;
- characterisation of particular waste streams;
- limited information on the Vulcan waste streams; and
- quantification of the material/chemical compositional information of waste streams.

110 These inventory uncertainties are discussed in more detail Section 3 of the 2020 Inventory Report [47]. In addition, a number of potential improvements to future UKRWI datasheet inventory estimates have been identified and put to DSRL Waste Operations [123], which focus on clarifying the assumptions made to derive the estimates, provision of time of arising data, and further development of the materials inventory. The D3100 LLW inventory will be revised periodically as improvements in waste stream inventory data are made as decommissioning operations proceed and additional characterisation is undertaken. However, the differences between the 2009 and 2020 inventory estimates, and the range of uncertainties that apply to the waste inventory that may require disposal, indicate some of the challenges that can arise if the authorised radionuclide limits are tied directly to a fixed historical inventory estimate. Hence, DSRL is applying to SEPA to vary the Permit to apply a risk-based approach to setting radioactivity limits for waste disposals in D3100, which will enable greater flexibility during waste acceptance to account for inventory uncertainty and to

optimise disposal of DSRL LLW (the SoF approach is discussed in Section 8). For example, the following radionuclides have been identified as those in the predicted D3100 average fingerprint with the greatest contribution to calculated performance, and therefore reducing inventory estimate uncertainty for these nuclides will produce the greatest benefit: ^{90}Sr, ^{137}Cs, ^{226}Ra, ^{234}U, ^{235}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{241}Am.

4.3.7 Context of Dounreay radioactive inventory

111 To put the Dounreay LLW inventory into context:

- The planning consent volume of LLW for disposal in the D3100 LLW facilities (175,000 m^3) is approximately 13.5% of the disposal capacity of Vaults 8 to 14 at the LLWR (1,297,000 m^3) [124, Tab.2].
- The best estimate D3100 LLW total activity given in Table 4.3 is approximately 4.4% of the total activity in the Case A inventory estimated for disposal at the LLWR in Vaults 8 to 14 [125, Tab.5.4].

112 The majority of the LLW activity to be disposed of at Dounreay (excluding the additional LLW/ILW boundary streams) derives from short-lived radionuclides (i.e. radionuclides with half-lives shorter than approximately 30 years). This activity will decay to insignificant levels than 300 years, while the facilities may still be under active institutional control (see Section 11).

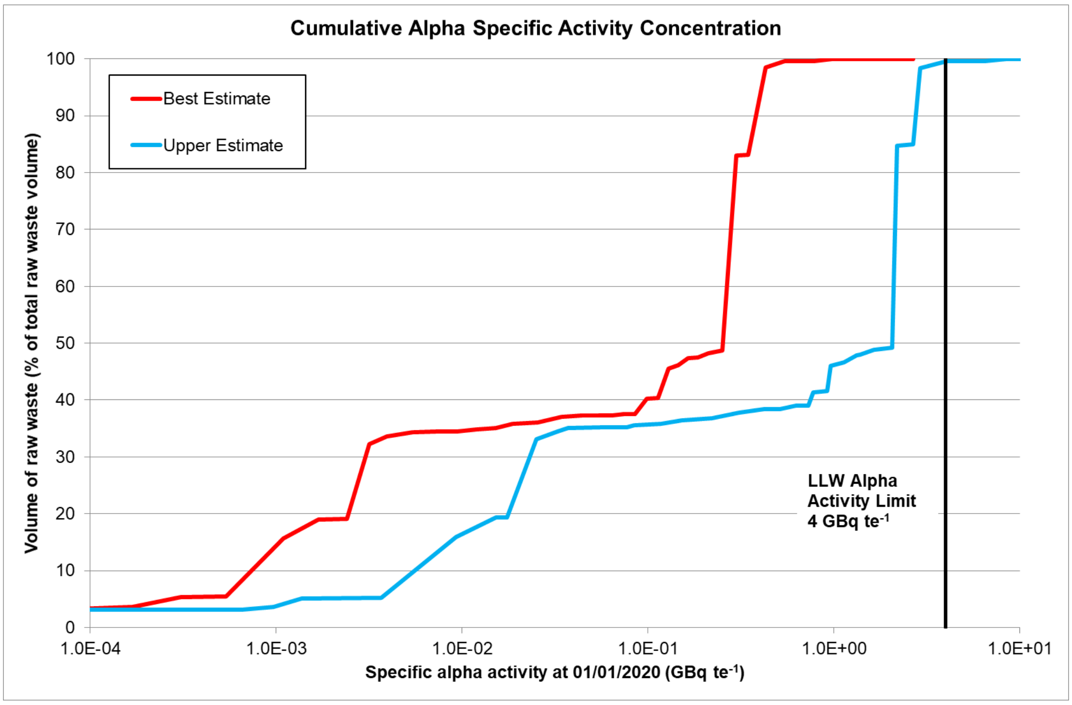
113 On the assumption that daughters with half-lives less than 3 months that are in secular equilibrium with their parent are excluded (see paragraph 61), the majority of the waste has an activity that is well below the maximum permissible activity limits for LLW defined by UK Government policy [3] and documented in Section 1.1. For LLW (Case C), the gross average specific activity of alpha-emitting radionuclides at 2020 is estimated to be 0.04 GBq te^{-1} (best estimate) and 0.14 GBq te^{-1} (upper estimate), well below the UK LLW alpha activity definition of 4 GBq te^{-1} defined in UK policy [3]. Similarly, the gross average specific activity of non-alpha-emitting radionuclides in LLW at 2020 is estimated to be 0.77 GBq te^{-1} (best estimate) and 4.07 GBq te^{-1} (upper estimate), also well below the LLW beta/gamma activity definition of 12 GBq te^{-1} [3]. For Demolition LLW, the best and upper estimate gross average specific activities are all below the Dounreay site definition of 0.01 GBq te^{-1} alpha and 0.4 GBq te^{-1} beta/gamma for Demolition LLW as defined in Section 1.1.

114 Figure 4.3 (best estimate values) shows that over 90% of the waste has beta/gamma activity levels between 4 x 10^{-4} GBq te^{-1} and 1.4 GBq te^{-1}, and over 80% of the waste has alpha activity levels between 6 x 10^{-6} GBq te^{-1} and 0.3 GBq te^{-1}. With such a large proportion of the waste having activity levels spanning a range of greater than four orders of magnitude, it is unlikely that the average activity level could be moved an order of magnitude without something radically changing the distribution of activity levels in radioactive wastes (i.e. it would require a significant volume of higher activity waste to move the average activity level several factors above the existing average). Similarly, it would take significant volumes of lower activity material to substantially reduce the average.

115 It can be seen from Figure 4.3 that a small number of waste streams included in the 2020 inventory do exceed the activity limits for LLW defined by UK Government policy [3]. For the best estimate activity levels there is only one stream, one of the Additional Streams at the ILW/LLW boundary, which exceeds the beta/gamma activity limit. Only if waste characterisation were to show that the current activity prediction was an over-estimate would this stream be acceptable for disposal in D3100. For the upper estimate activity levels, there are several waste streams exceeding the limits; these are primarily from the Additional Streams and the waste streams from the Vulcan NRTE site. The characteristics of these streams are documented in Section 5 of the 2020 Inventory Report [47].

116 The alpha content of the waste is consistent with the alpha content of waste suitable for near-surface disposal used in several other countries (as discussed in [58]). However, while the average alpha content of the Dounreay waste is comparable to that to be disposed of in near-surface facilities in other countries, the beta/gamma content of the Dounreay waste is considerably lower. This is because facilities in other countries accept wastes with concentrations of short-lived beta/gamma activity that are much higher than the UK definition of LLW owing to the potential for engineering to contain this activity until it has decayed.

(a)



(b)

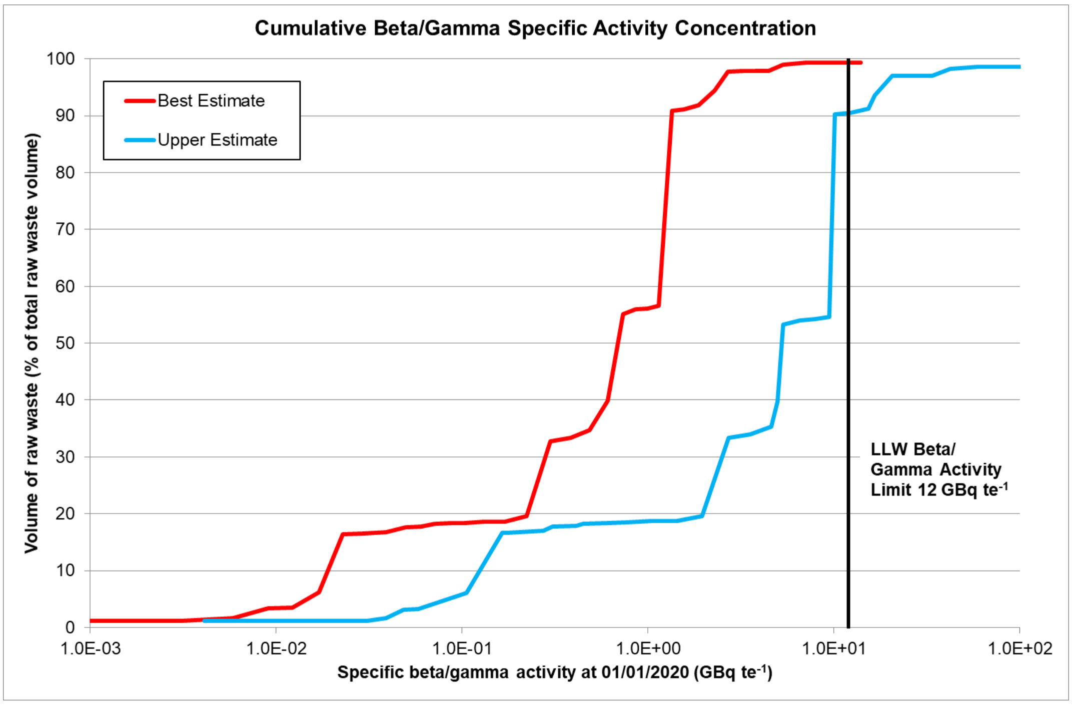


Figure 4.3: Percentage of raw total waste volume (LLW and Demolition LLW) against specific activity for (a) total alpha content, and (b) total beta/gamma content, at 1 January 2020 using the best and upper estimate activities as reported in [47]. Activity limits for LLW are those defined in UK policy [3]; any waste over the defined limit would not be accepted for disposal in D3100.

4.4 Waste Acceptance

GRA 6.4.26-27	**Requirement R13: Waste acceptance criteria**. The developer/operator of a disposal facility for solid radioactive waste should establish waste acceptance criteria consistent with the assumptions made in the environmental safety case and with the requirements for transport and handling, and demonstrate that these can be applied during operations at the facility.
GRA 6.4.28	The factors that affect the performance of the waste before and after disposal, and that need to be covered by the acceptance criteria, include the radionuclide content, the chemical and physical form and durability, the susceptibility to microbial action, the thermal and radiation stability, and the mechanical stability.
GRA 6.4.29(a)	Include requirements in the acceptance criteria that ensure as far as reasonably practicable that all waste accepted for disposal is passively safe. The chemical and physical form of the waste should limit detrimental chemical or microbial interactions, and should restrict the release of radionuclides into the disposal environment, in accordance with the assumptions of the environmental safety case. The radiation and heat resistance of the waste form should be in accordance with the assumptions of the environmental safety case. The waste package should have sufficient mechanical stability to withstand the conditions of transport and handling, and to meet any assumptions regarding structural integrity made in the case.
GRA 6.4.29(b)	Demonstrate that the possibility of a local accumulation of fissile material, such as to produce a neutron chain reaction, will not arise.
GRA 7.3.31	Consider the issue of a criticality event, although a simple analysis should be sufficient to demonstrate that such an event will not occur.
GRA 7.2.18	The environmental safety case will provide an input to deriving facility-specific regulatory limits and conditions, and should help to underpin the developer/operator's waste acceptance criteria and emplacement requirements.

117 DSRL has developed a waste acceptance process for D3100 to ensure that wastes accepted for disposal in the facilities are consistent with the ESC and underpinning safety assessments, regulatory requirements and guidance, and DSRL operational requirements. This process is illustrated in Figure 4.4 and ensures that disposals are undertaken in accordance with key underpinning assumptions in this ESC. Key to the process is a set of Waste Acceptance (WA) Rules that map waste properties to assumptions in the ESC and underlying reports [54]. The assessments of operational and post-closure safety inform the development of waste acceptance rules. For example, assessment of operational waste package handling activities informs the specified waste package surface dose rates. Radionuclide waste acceptance rules are based on assessment screening to identify potentially significant radionuclides, both from the perspective of their proposed total inventory and the intrinsic hazardous properties associated with a given radionuclide. Similarly, the predicted inventory of NoRaH materials is screened based on *a priori* identification of certain substances as hazardous. Operational/handling and post-closure/release safety are then

assessed specifically for those NoRaH substances that are expected to be present in greater amounts (see Section 7.10).

118 The Dounreay site has a separate EASR 18 Permit that permits transfer of waste from the site to D3100 for disposal. DSRL has established a separate D3100 Compliance team, independent from site waste consignors, to manage the facilities. Acceptance of wastes into D3100 is conditional on site waste consignors demonstrating that the wastes are compliant with the D3100 WA Rules. This condition is implemented on the Dounreay site through the DSRL Waste Management Process, which the D3100 Compliance team works to ensure is consistent with the D3100 WA Rules. The key documents in the site Waste Management Process are the Dounreay Waste Manual (MAN 2007) [107], the PSWPs [114], the procedure for the Management, Control and Consignment of Solid Low Level Waste (PRC 2158) at Dounreay [126], and the LLW CfA [112]. In addition to the D3100 WA Rules, key documents for D3100 include the Operational Management Plan (OMP, [116]), the Load Management Plan (LMP, [127]) and the Waste Compliance Test Plan (WCTP, [128]).

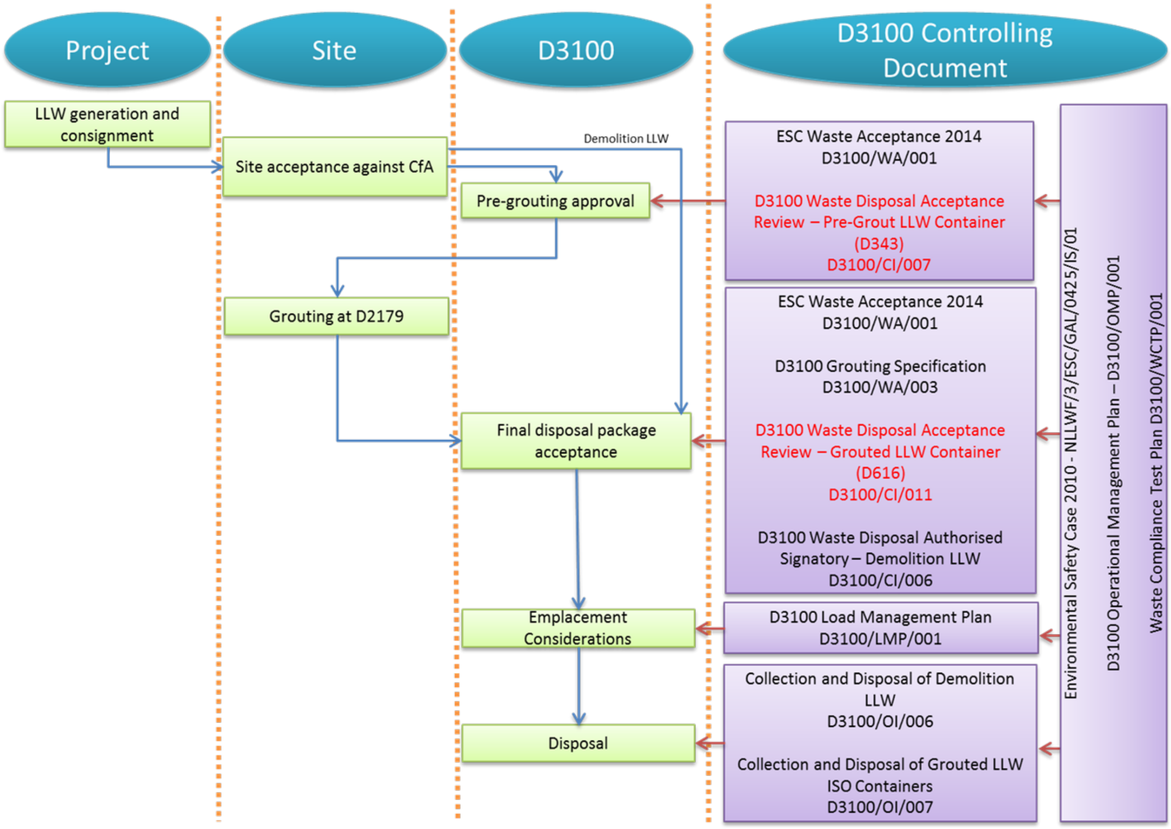


Figure 4.4: DSRL and D3100 waste management and acceptance process [116, Fig.3.1].

119 An initial set of waste acceptance requirements, specified as WAC for D3100, was developed in 2009 for discussion with SEPA [129]. The requirements were developed further [130] to accompany Issue 1 of ESC 2010 [28] when applying for authorisation. The issued RSA 93 Authorisation [12] for D3100 contained Authorised WAC, and so the D3100 requirements were revised as WA Rules for consistency

with the Authorised WAC, prior to the start of operations. The WA Rules were presented in Waste Acceptance 2014 [131] in support of ESC 2010 Issue 2 [29]. The WA Rules contain additional requirements to the Authorised WAC to cover issues not covered by the WAC or that are reflective of non-EASR 18 requirements. For example, the Authorisation has a condition that the facilities must be consistent with the ESC, but does not contain a WAC specifying the composition of the waste conditioning grout. Nevertheless, the modelling in support of the ESC makes assumptions about the grout and these assumptions are reflected in a WA Rule. The WA Rules in Waste Acceptance 2014 are consistent with the Authorised WAC in the current D3100 EASR Permit [14] and the D3100 waste acceptance process is consistent with the WA Rules.

120 As part of the DSRL work programme to consider a risk-based approach to setting radioactivity limits for waste disposals in D3100, the original intent of the WA Rules and the safety (or other) functions that they were intended to fulfil was reviewed. The findings of an extensive verification exercise undertaken to assess compliance of the wastes disposed of to-date with the existing WA Rules [132] were taken into account. The review [133] concluded that the WA Rules in Waste Acceptance 2014 [131] remain generally appropriate, although some small textual changes were recommended mainly for the sake of clarity. Thus, DSRL has developed a revised set of WA Rules (WA Rules 2020) [54] for D3100 that implement the recommended changes and incorporate:

- a risk-based approach to setting radioactivity limits for waste disposals in D3100 through application of a SoF approach [49], instead of setting limits based on the latest predicted inventory (this is discussed further in Section 8);
- revisions to the wording on minimisation of voidage to include both accessible and inaccessible voidage and to place an upper limit of 10% on inaccessible voidage above which a variation[17] must be sought [132];
- revisions to simplify WA Rules that pertain to management of non-radiologically hazardous (NoRaH) materials [53] (see Section 7.10); and
- updated controls on waste packages containing fissile material, based on a revised criticality safety assessment [52] (see Section 7.11).

121 The WA Rules 2020 report sets out and justifies the series of conditions that need to be met during waste consignment and acceptance to comply with the assumptions in this ESC, the Nuclear Safety Case for D3100 [55], and the planning application [16]. Effectively, the WA Rules are a statement of ‘what’ needs to be done to ensure that the facilities are operated safely and that long-term environmental impacts are minimised; the details ‘how’ these can be met are covered separately in D3100 waste acceptance specifications and processes. The WA Rules have been designed to meet all of the relevant GRA requirements [19, particularly ¶6.4.28 and ¶6.4.29] and be consistent with the IAEA requirements [23].

[17] A variation process is DSRL terminology for an exception process.

122 The D3100 WA Rules are grouped according to eight aspects as follows:

- WA Rule 1: Compliance with the waste acceptance process;
- WA Rule 2: Physical characteristics of the waste packages;
- WA Rule 3: Chemical characteristics of the waste packages;
- WA Rule 4: Biological characteristics of the waste packages;
- WA Rule 5: Radiological characteristics of the waste packages;
- WA Rule 6: Criticality safety controls;
- WA Rule 7: Quality assurance; and
- WA Rule 8: Changes to the Waste Acceptance Rules.

123 The revised WA Rules for application in the D3100 waste acceptance process, along with a summary of the justification for each Rule and their relevance to different aspects of safety (transport, operations and post-closure), are presented in Appendix A. The WA Rules in Appendix A have been consolidated into one table – a separate table for each waste type was presented in ESC 2010 [29]. The revisions made since ESC 2010 reflect changes as a result of learning from operational experience, as well as changes resulting from updates to legislation and guidance. All the proposed revisions have been developed in discussion with SEPA through regular technical exchange meetings. WA Rules 2020 may need to be revised in the future if modified or additional WAC are included by SEPA in the Permit variation being sought here that require flow-down into the D3100 waste acceptance process.

FP.3	As necessary, review and revise the WA Rules for D3100.

4.5 Compliance with the WA Rules and Authorised WAC

GRA 6.4.30	Make sure that the radionuclide content and composition, including the fissile content, of waste consignments received for disposal are sufficiently well characterised to comply with the conditions of the authorisation under RSA 93[18].

124 As the operator of the D3100 facilities, DSRL needs to be satisfied that potential waste consignments meet the WA Rules. The OMP [116] identifies how the facilities are managed in compliance with the EASR 18 Permit for D3100. The OMP takes account of load management considerations, leachate management, water management, packaging, criticality safety, WA Rules and Authorised WAC, waste receipt and disposal, capping, environmental monitoring, records management, and staff training.

18 RSA 93 has now been replaced, in Scotland, by EASR 18. However, the GRA has not yet been updated to reflect this. The GRA text has been quoted verbatim here and in the rest of this ESC, but any reference to RSA 93 should be taken to mean EASR 18.

125 Processing of solid LLW involves the generation of records covering all stages of the process. Electronic records of consigned LLW and Demolition LLW are kept by DSRL on the Dounreay DMS. Conformance to the WA Rules (and thus Authorised WAC) is assured by the D3100 Compliance Team through inspection of the evidence pack submitted by consignors during the waste acceptance process. The D3100 WCTP [128] details the methodologies employed by DSRL to demonstrate that the Dounreay site's Waste Management Process produces waste packages that are compliant with the WA Rules. The WCTP complies with EASR 18 Permit Condition 5.1 [14] to prepare, implement and maintain a programme of waste compliance testing.

126 The ability of DSRL to also conduct testing and verification retrospectively was demonstrated by a major exercise conducted between May 2018 and January 2020 to verify that the waste already disposed of to D3100 met the WA Rules [132]. The verification project was initiated when a HHISO containing sealed waste crates was rejected for disposal as the inaccessible voidage had not been appropriately minimised (i.e. it was not demonstrably applying BPM). It was recognised that several packages containing such waste crates had already been disposed of, and the need to verify all of the disposed waste against the WA Rules was identified. Outcomes of the work included recommended clarifications to some of the wording of the WA Rules (see Section 4.4 above), and an options assessment that concluded that the optimum recovery option for the existing HHISOs containing sealed waste crates in the LLW vault was to re-distribute them throughout the vault [134]. SEPA has now approved redistribution of these containers within the LLW vault [135].

FP.4 As necessary, review and revise the Operational Management Plan and supporting documents for waste acceptance in the D3100 disposal facilities.

5 FACILITY DESIGN

127 This section addresses the requirements in the GRA [19] related to the design of D3100. The international and national principles that apply to the design of near-surface disposal facilities are considered first, followed by a description of the facilities, how the design and build activities have been carried out, and how optimisation has been taken into account in the project so that the design is considered to be optimised.

5.1 Design Principles

GRA 6.2.27	All work that supports the ESC needs to follow good engineering practice.
GRA 6.4.15	Depending on the hazard presented by the waste to be disposed of, adopt an iterative approach to facility design and development of the environmental safety case as results are progressively obtained from the site characterisation activities.
GRA 6.4.17	The approach to the use of the site and to facility design, construction, operation and closure should be proportionate to the hazard presented by the waste that the facility is intended to receive.

5.1.1 International design principles and design process

128 The IAEA has set out a fundamental safety objective and ten associated safety principles to protect people and the environment from harmful effects of ionising radiation ([57]; Tab.3.1). Five of these IAEA principles are of particular relevance to the design for disposal facilities:

- Principle 5: Optimisation of protection. Protection must be optimised to provide the highest level of safety that can reasonably be achieved.
- Principle 6: Limitation of risks to individuals. Measures for controlling radiation risks must ensure that no individual bears an unacceptable risk of harm.
- Principle 7: Protection of present and future generations. People and the environment, present and future, must be protected against radiation risks without placing a burden on future generations.
- Principle 8: Prevention of accidents. All practical efforts must be made to prevent and mitigate nuclear or radiation accidents (i.e. defence in depth).
- Principle 9: Emergency preparedness and response. Arrangements must be made for emergency preparedness and response for nuclear or radiation incidents.

129 The IAEA has published safety requirements for disposal of radioactive waste that are consistent with the above principles [23]. The IAEA safety requirements relevant to the design of a disposal facility can be summarised as providing for:

- isolation of the waste to meet safety targets;
- minimisation of the need for maintenance and control after closure;

- minimisation of environmental impacts;
- use of engineering and engineered barriers to achieve the above;
- allowance for monitoring without compromising safety;
- allowance for retrievability, if desired, without compromising safety; and
- implementation of design control to evaluate the potential impact of design changes on safety.

130 In addition to safety requirements and guidance, the IAEA has published a number of reports that go into more detail on technical design considerations for near-surface disposal facilities (e.g. [136; 137; 138]). The design objectives set out by the IAEA in [136] are consistent with those set out in the IAEA fundamental safety principles. However, the technical design considerations [136], and the more recent design principles and approaches [138], give more detail on factors to be considered during the design process. These factors were taken into account in the D3100 design process (e.g. see the D3100 Design Justification Report [139]), and will continue to be so.

5.1.2 UK design requirements

131 The UK regulatory expectations for the design of a radioactive disposal facility, as set out in the GRA [19] and repeated in the boxed text in this section, are consistent with the IAEA principles. However, in comparison to the IAEA requirements, those in the GRA are more specific with regard to isolation, as they relate to UK-specific criteria for radiological protection. The GRA requirements also address the principle of optimisation specifically. Another difference is that the GRA requires engineering, specifying that the safety case must rely on multiple components. The IAEA requirements [23] are more general with regard to engineered barriers, although the IAEA technical considerations for design (e.g. [136; 137]), do cover performance objectives. The GRA also specifically requires the design to consider the implications of gas generation and migration, and to consider heat generation and criticality. These issues are covered in this section.

5.1.3 Approach to design of D3100

132 The main design objective for D3100 was to meet the UK radiological protection constraints and objectives. The facilities are designed to achieve zero releases of radioactivity to the environment during normal operations, other than through shine from the outside of packaging, and to provide high levels of containment and isolation following closure.

133 The design process is iterative and multi-staged, and the design continues to evolve as D3100 operational experience is gained and the knowledge base for worldwide disposal facilities develops. The IAEA design principles report [138] divides the design process into five main phases: generic design; conceptual design; technical design (referred to as basic design in [136]); detailed design; and closure design. These phases are illustrated in Figure 5.1, which also indicates the relationship with

the safety assessment and licensing process. The equivalent stages in the D3100 project are indicated on Figure 5.1:

- **Generic design.** D3100 project Stage 1 used a generic design in support of the Run 1 PA and the BPEO study [7], which identified the Dounreay site. The approach at the generic design stage was to review international practice and guidance [140], and extant UK practice (e.g. [141; 142]), and adopt similar practice [143].
- **Conceptual design.** A conceptual design (an early version of the D3100 "scheme design") for near-surface facilities was developed, together with the Run 2 safety assessment and available knowledge concerning site characteristics, to support site selection.
- **Technical design.** Under Stage 2, the D3100 project refined the conceptual design to develop the technical (basic) engineering design (referred to as a "scheme design" by DSRL), together with further, more detailed site characterisation (see Section 6) and safety assessments (see Section 7). The scheme design was used to support the RSA 93 Authorisation application and the Run 3 PA. The design refinement involved detailed design studies covering optimisation[19] and consideration of BPM, environmental impacts and sustainable development [16; 144; 145; 146; 147].
- **Detailed design.** The design was further developed during the design-and-build contract under Stage 3 of the project [148; 149], with the as-built detailed design assessed in the Run 4 PA. It is the as-built design [51; 150] that is described in this ESC and that has been assessed in the latest iteration of the D3100 PA.
- **Closure design.** Technical (scheme) designs for closure and capping of the facilities have been developed; these will be developed in more detail as the time to close vaults in the D3100 facilities approaches.

134 Optimisation and BPM studies will be ongoing throughout the operation and closure of the facilities. Indeed, it is recognised that the detailed design continues to evolve, as operational experience leads to changes in the existing vaults and improvements in the design for vaults yet to be constructed; the evolution of facility design and its current status are documented in a living summary design report [150]. This deviates from Figure 5.1, as the detailed design is not fixed and the PA is run more frequently than just at closure. The approach to, and progression of, these optimisation studies

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19 In paragraph 6.3.58 of the 2009 GRA [19], the concept of 'optimisation' is described as being 'about finding the best way forward where many different considerations need to be balanced. Relevant considerations include, for example, economic and societal factors, and the requirement to manage any non-radiological hazards'. This concept replaces that of BPM set out in an earlier version of the GRA. However, the concept of BPM is still used in Scotland, and more recent guidance than the GRA [104] explicitly discusses application of BPM to discharges from solid waste disposal facilities. In order to maintain consistency with both sets of guidance when discussing previous work and current work, both terms are used as appropriate in this ESC.

is discussed from paragraph 200 onwards to the end of this section. The preceding references in the paragraph above are primarily to regular reports that have been produced to summarise the outputs of these studies. The latest optimisation report [51] has been produced to support this ESC by summarising work up to summer 2020. The summaries will continue to be routinely updated as work progresses.

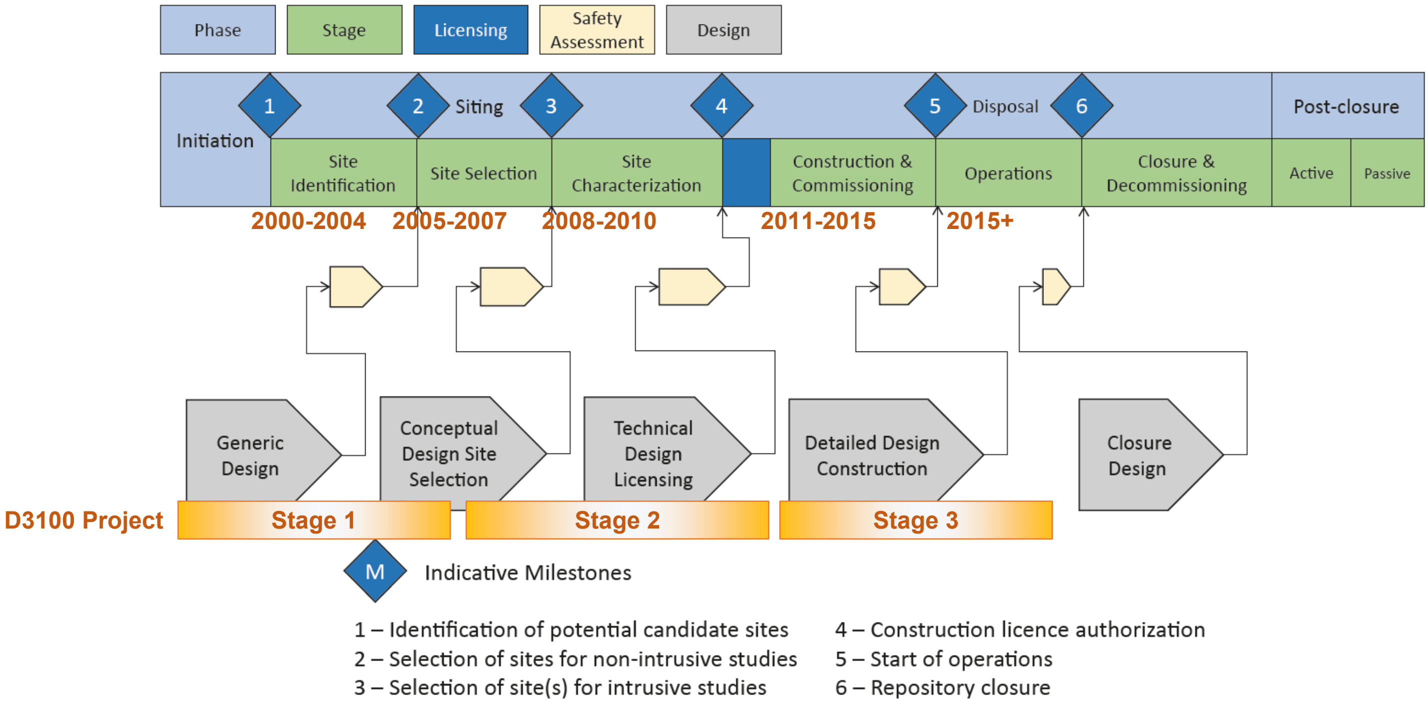

Figure 5.1: Generic disposal facility programme lifecycle and associated design stages aligned to indicative project milestones, as developed by the IAEA [138, Fig.4]. The equivalent D3100 project stages have been overlaid.

5.2 Description of D3100

GRA 6.4.16	**Requirement R12: Use of site and facility design, construction, operation and closure.** The developer/operator of a disposal facility for solid radioactive waste should make sure that the site is used and the facility is designed, constructed, operated and capable of closure so as to avoid unacceptable effects on the performance of the disposal system.
GRA 6.4.18	Demonstrate that the proposed location of the facility within the site is large enough to accommodate the categories and quantities of waste to be disposed of, whilst being far enough away from geological media of less suitable characteristics.
GRA 6.4.20(b)	Where backfilling is used, show that methods and materials have been chosen that are compatible with the waste form and the geological setting, and that provide an overall system performance consistent with the claims made in the environmental safety case.

GRA 6.4.21	In design and construction, take into account a number of effects that may arise from properties of the waste, including: - gas generation through microbial, chemical, or radiolytic action, or as a result of radioactive decay; - heat generation through microbial or chemical action, or as a result of radioactive decay; …
GRA 6.4.22	Gas generation within the disposal facility can lead to gas movement through and around the facility. Considerations will need to include any venting of gases, both those presenting a radiological hazard and those presenting other hazards such as explosions or asphyxiation, to the atmosphere that may occur and any implications this may have for people and the environment.
GRA 6.4.24	At the design stage, and periodically during the lifetime of the facility, demonstrate that it is able satisfactorily to close the disposal facility and, where relevant, seal any preferential pathways that will or may be introduced as a result of the siting, construction and operation of the disposal facility.
GRA 7.2.6(c)	The ESC should describe all aspects that may affect environmental safety, including the design of the facility and the techniques used to construct, operate and close it.
GRA 7.2.17(b)	Operational decisions and practices should be consistent with the ESC.

135 The concept design [143] for a shallow below-surface[20] facility, developed during Stage 1 of the project, considered the waste to be grouted into HHISO-type containers that are stacked in concrete vaults. At closure, a cap is emplaced over the vaults to isolate the wastes and limit water infiltration. This grouting of wastes and the use of concrete vaults is consistent with LLW disposal practice elsewhere, including at the LLWR, the Centre de l'Aube facility in France, and the El Cabril facility in Spain. In Stage 2 of the D3100 project, the scheme design was developed – that design, with minor modifications and details developed during the design-and-build phase of the project, has been adopted for the Phase 1 vaults. Schematic illustration of the as-built facilities are shown in Figure 5.2 for LLW and Figure 5.3 for Demolition LLW. Elements of the scheme design, such the vault layout, will be subject to review, and design details may also be reviewed as a result of learning from experience and ongoing optimisation. The key features and components of the design relevant to radiological performance are summarised in Table 5.1. The design meets the requirements of this ESC and those for operational safety (see [30]), and it complies with the assumptions made in the quantitative safety assessment (see Section 7).

20 "Below-surface" refers here to a facility that is located just below the groundwater surface, with the top of the waste stack a few metres below the ground surface. It is synonymous with various terms used in Stage 1 reports, including "near-surface", "sub-surface", and "below-ground".

Table 5.1: Design components of D3100 and their associated functions.

Feature / Component	Description	Function
Location	Adjacent to the eastern boundary of the existing Dounreay nuclear licensed site.	Optimised balance between short-term environmental impacts and long-term sea inundation and erosion potential.
Depth	Top of wasteform located at least 4 m below ground surface (i.e. largely below near-surface higher groundwater flow). Eight-high container stacking increases depth and reduces footprint compared to four-high stacking.	Optimum balance between cost, short-term environmental impact, likelihood of intrusion, and potential releases to the surface environment.
Waste Conditioning	Cement grout (LLW only).	Shielding. Low permeability/void removal. Chemical conditioning – alkaline environment to provide a retarding medium.
Waste Package	LLW – ISO containers or equivalent. Demolition LLW – polypropylene bags.	Allows simple waste handling and placement of containers – LLW vaults. Sufficiently robust for local transportation.
Vault Backfill	Cement grout as necessary where gaps exist between containers (LLW vaults). Granular material (Demolition LLW vaults).	LLW vaults – low-permeability, void removal and chemical conditioning. Demolition LLW vaults – eases emplacement and enhances long-term stability.
Base and Walls	Low-permeability durable concrete.	Reduce water ingress into the facility. Operational stability.
Drainage / Exterior Backfill	Void between the walls of the vaults and the host rock. Filled with aggregate during operations and on closure. Split-level drainage system, in the form of channels around the facilities to pumps, diverts groundwater and surface water flow away from the excavations to discharge points in the enhanced geosphere.	Keep the interior of the facility dry during operations. Manage water flow to allow monitoring and control of water during operations. Provides hydraulic cage around vaults on closure.
Lid and Cap	Mixture of layered materials, including low-permeability lid, anti-intrusion layer of slabs of	Minimise upward migration of water from the facilities to the surface. Deter inadvertent and deliberate intrusion.

Feature / Component	Description	Function
	rock, low-permeability layer, and soil.	Accommodate settlement and small volume of gas generation from the wasteform.
Enhanced Geosphere	Layer of excavated material, approximately 5 m thick, deposited between the excavations and the cliffs.	Elevation of the soil zone above the water table. Minimise upward migration of water from the facilities to the surface. Disperse D3100 passive upper level drainage system and pump system discharges. Ensures discharges are directed away from Landfill 42.

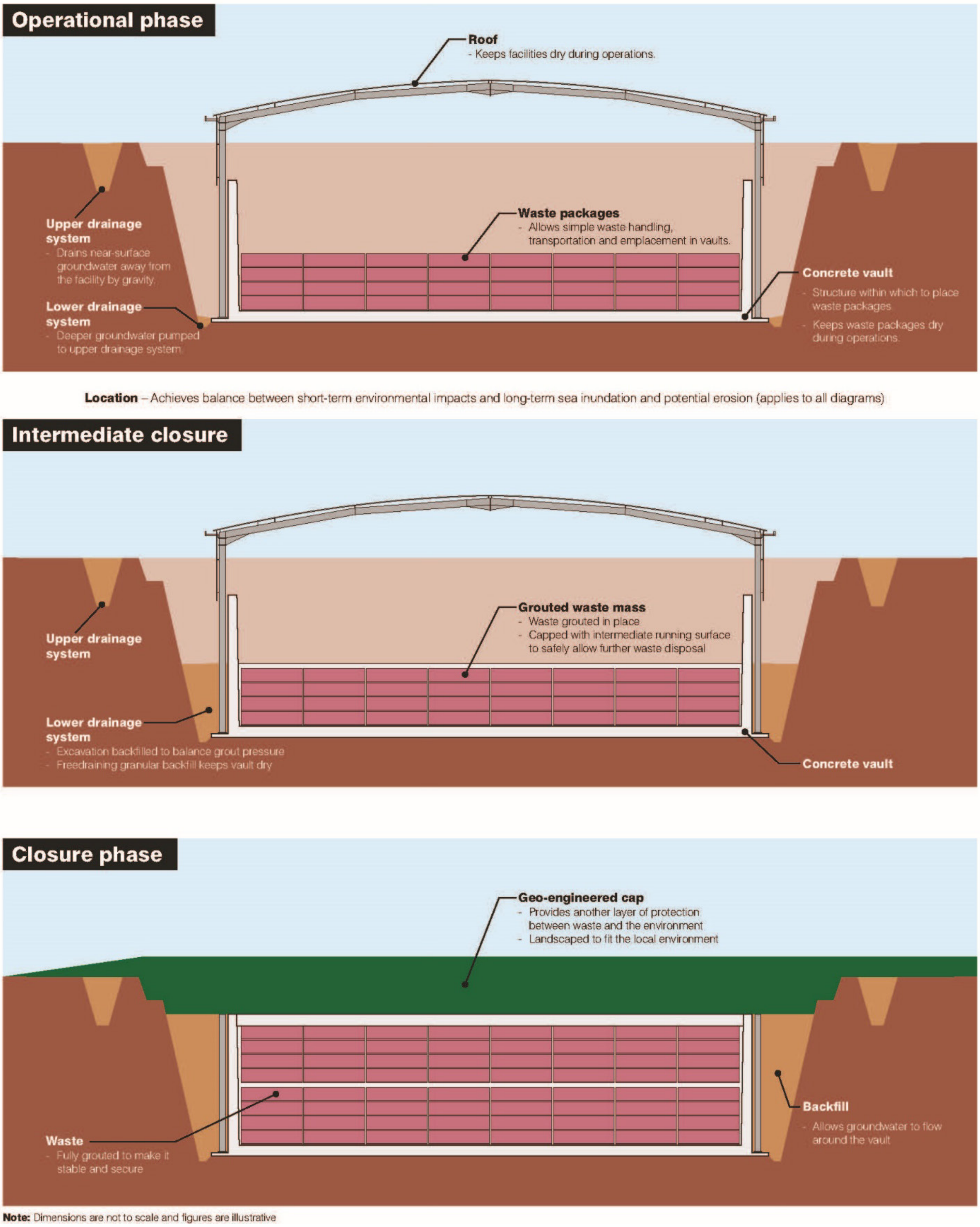

Figure 5.2: Illustrations across the width (east to west) of a single disposal LLW vault during the operational phase (top), at intermediate closure when HHISOs are stacked four-high across the floor and a new running surface is laid (middle), and after closure and capping (bottom). The red rectangles illustrate individual LLW containers stacked in the vaults, eventually in eight-high stacks.

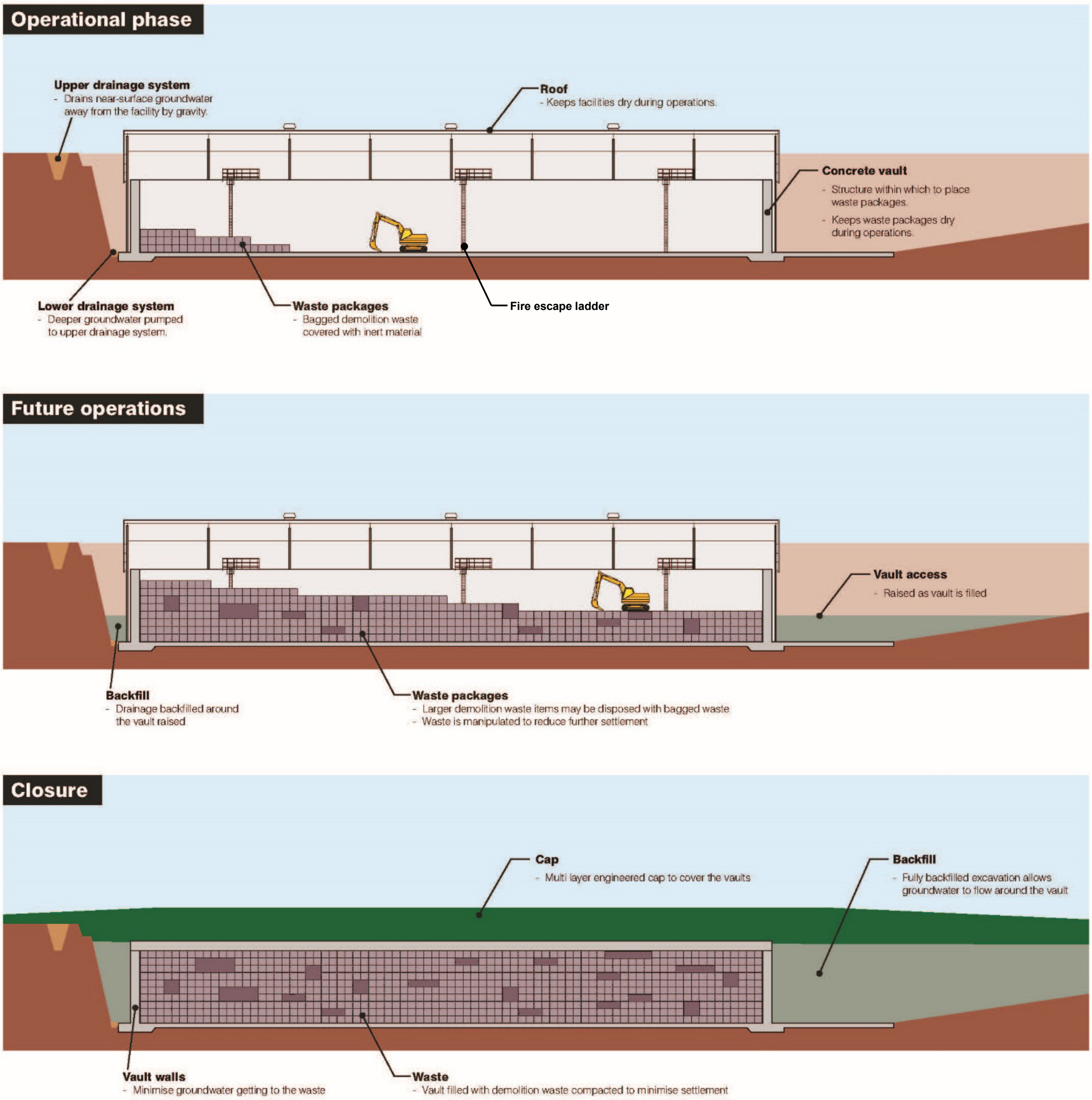

Figure 5.3: Illustrations across the length (south to north) of a single disposal Demolition LLW vault during the operational phase (top), at a future operational point as waste continues to be emplaced and settlement reduced (middle), and after closure and capping (bottom). The grey cubes illustrate individual Demolition LLW bags, along with the possible presence of occasional large non-bagged waste items.

5.2.1 Location and size of the vaults

136 The Stage 1 BPEO study identified disposal in near-surface facilities on UKAEA-owned land (now NDA-owned land) at Dounreay as the preferred option [7]. This option was selected as the long-term LLW management strategy [5]. The exact

location of the facilities on NDA-owned land at Dounreay has been developed through a series of optioneering workshops as described in the 2011 optimisation report for D3100 [148, Ch.3] and summarised in [151; 152] and below.

137 Prior to Stage 1, a preliminary options analysis as an input into the planning of site characterisation studies considered the NDA-owned land at Dounreay divided in to the eight areas shown on Figure 5.4. This analysis identified the area around the east end of the old airfield runway as the most suitable location for the disposal facilities at Dounreay. During Stage 2, this options analysis was revisited in light of more information being available on issues such as geology and hydrogeology, radiological safety, environmental impacts, and local stakeholder views. The following issues were considered in the Stage 2 site selection analyses:

- stakeholder views on site location – particularly those of the Highland Council and near-neighbours;
- lifecycle environmental issues – visual, ecological, archaeological, air quality and water quality impacts, property blight, and land character;
- technical issues – hydrogeology, climate change, and water management;
- value – capital and operating costs;
- construction issues – waste creation and scheduling issues; and
- transportation issues – construction and operational periods.

138 As a starting point in the Stage 2 analyses, DSRL considered that siting the facilities in a location that is likely to be eroded owing to sea-level rise and coastal erosion in the next few thousand years would be unlikely to be regarded by SEPA as representing BPM. Radioactive waste management principles, as emphasised by the GRA [19], favour containment of radioactivity for as long as practicable, as opposed to dispersion and dilution. However, estimates of the radioactive waste inventory in 2009 at the time of the Stage 2 development work showed that the radioactivity of the Dounreay LLW will decline sharply in the next few hundred years [122, Fig.4.3] and the average alpha activity in the LLW vaults would be around the level of background alpha activity in Dounreay soils at around 10,000 years after closure. (The distribution of the radionuclides making up the total alpha activity will be slightly different in the LLW compared to the soil, but radiological impacts from the two media are comparable – long-term doses to the borehole resident from inadvertent human intrusion in Section 7 are mainly from radon and are generally lower than the doses from background radiation.) In its siting analyses, therefore, DSRL adopted a siting objective to reflect land where disruption of the facilities by sea-level rise and coastal erosion over the next 10,000 years is considered unlikely. This siting objective is shown as a red line in Figure 5.4 and ruled out a large part of NDA-owned land to the north of this line and adjacent to the coast from being selected as a location for the facilities. The position of this line in terms of possible erosion rates and sea-level changes was corroborated by a review of the literature on climate change and coastal erosion [153]; see also paragraph 325.

139 The siting analyses considered NDA-owned land to the south of the red line in detail. Not all of the issues listed in paragraph 137 discriminate significantly between the different locations considered. For example, based on existing knowledge of local

geology and hydrogeology, the technical assessments supporting the BPEO [7] demonstrated that long-term safety requirements could be met for LLW disposal facilities built almost anywhere on NDA-owned land at Dounreay.

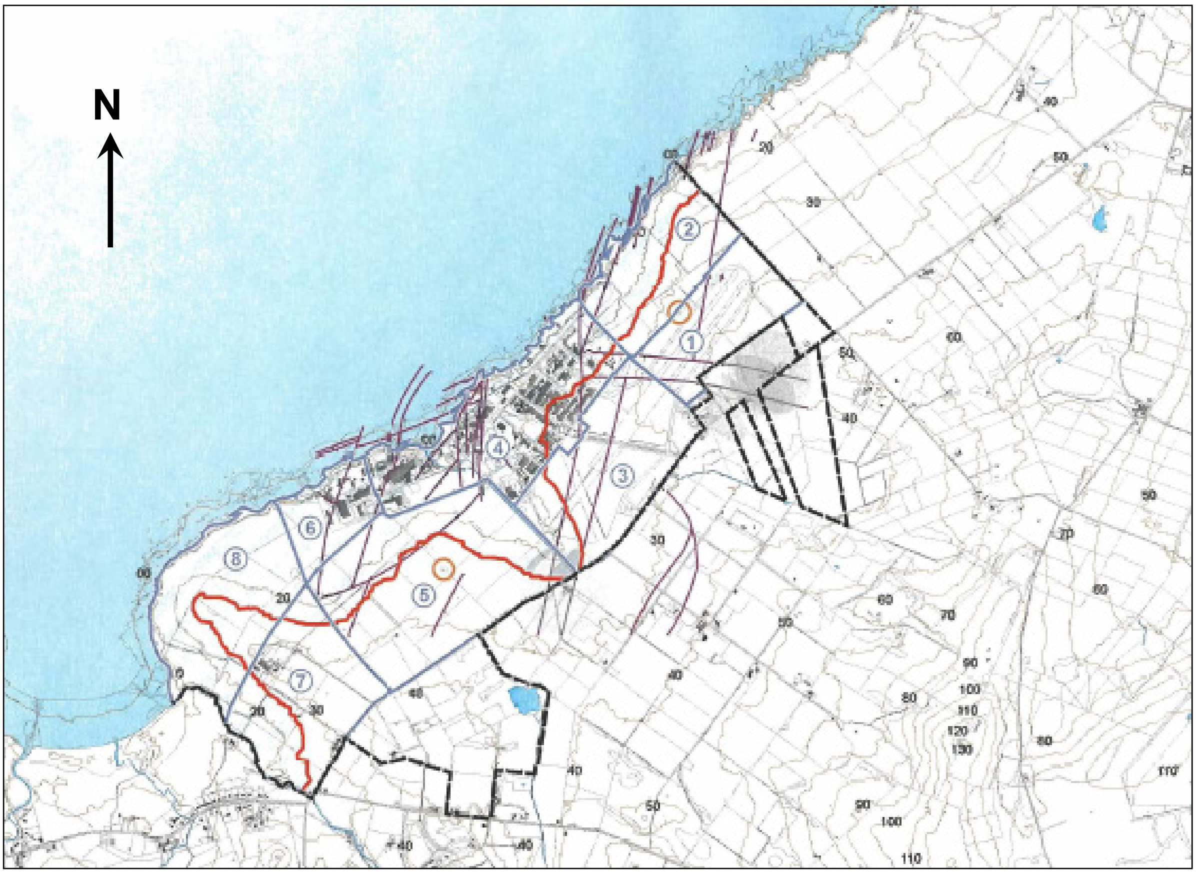

Figure 5.4: Map of Dounreay licensed site and surrounding area showing NDA-owned land considered in siting analyses (black dashed boundary), the division of this land into numbered areas for comparison in the siting analyses, and the red line used as a siting objective to allow for sea-level rise and coastal erosion over the next 10,000 years [151, Fig.2]. Purple lines indicate faults based on knowledge as of 2006, and red circles indicate 50-m consultation zones around ancient monuments, as considered in 2006 and 2007 siting analyses.

140 Areas west and inland of the licensed site are adjacent to Sandside Bay and were generally not favoured, mainly owing to potential environmental impacts on a large number of local receptors, and also for the increased spread of the Dounreay footprint that would result through the creation of facilities isolated some distance from the existing licensed site. Areas to the south and south-west of the licensed site are also not favoured, mainly owing to potential environmental impacts. These areas are generally open areas of good arable ground (compared to the rough grazing nearer the coast) and are highly visible from all around the local area. Placing the facilities on the existing licensed site would minimise near-term environmental impacts, but there would not be sufficient suitable space on the licensed site to construct the vaults [152].

141 The optimum area selected in all of the siting analyses conducted was concluded to be to the east of the licensed site. Two options to the east of the licensed site were compared in the initial Stage 2 siting analysis: an area next to the licensed site immediately south of the red line; and an area further inland on the eastern end of the old runway. The area nearest to the site was selected as it significantly reduced the visual, noise and air quality impacts on local stakeholders living just south of the old runway, and reduced the potential for property blight. Selection of this area also accorded with the views expressed during stakeholder consultation exercises that the facilities should be as close to the licensed site as possible. The slight increase in elevation and distance from the sea associated with the area on the old runway was not considered a significant factor in demonstrating the safety of the facilities, particularly given the uncertainties in climate change models.

142 In summary, the location selected for D3100 adjacent to the eastern side of the existing licensed site achieved a balanced compromise between various physical constraints and a range of environmental and stakeholder issues. It minimised the spread of the Dounreay footprint, lying as close to the existing licensed site and as far from nearest neighbours as is practical, and is visually unobtrusive.

143 Following the initial Stage 2 siting analysis, site characterisation data obtained in 2006/07 indicated that the major faults in the area have slightly different locations than previously thought. DSRL revisited the Stage 2 siting analysis and made minor adjustments to the precise location of the facilities to avoid locating the facilities directly above a major fault zone (the Geodh nam Fitheach Fault Zone – see paragraph 242). DSRL has aimed to avoid siting the facilities on known major geological faults owing to their potential to have increased water flows relative to the surrounding rock mass which could have a negative impact on ease of construction and operation and on long-term safety. The presence of major faults within the footprint of the facilities would also introduce geotechnical risk for the construction, which should be avoided where practicable. In a review of the siting analyses in November 2007, the facilities were sited as far from the coast as practicable, while avoiding this major fault zone. The vaults were deepened, thereby reducing their footprint, and aligned with their long axes parallel to the predominant groundwater flow direction; this is the location and layout put forward in the 2008 planning application [16]. Site characterisation conducted since 2007 has not identified any need to make further adjustments of the vault layout. However, the design-and-build studies resulted in a small repositioning of the vaults, with the Phase 1 vaults constructed slightly further back from the coast. This repositioning is still faithful to the considerations of the red line and the structural geology (see Figure 5.4), but pairs the LLW Vaults and Demolition LLW Vaults together in order to facilitate phased construction. The repositioning does not compromise environmental safety [148; 154].

144 Figure 5.5 shows an illustrative plan view of D3100, showing the existing Phase 1 vaults (and the enhanced geosphere and stockpile areas discussed later). There is still scope for further movement or rearrangement of future vaults within the D3100 site footprint, if required. The illustration shows a proposed layout for future Phase 2 and 3 vaults, if these are required. However, as discussed in paragraph 13, the order of future vault construction phases is under review.

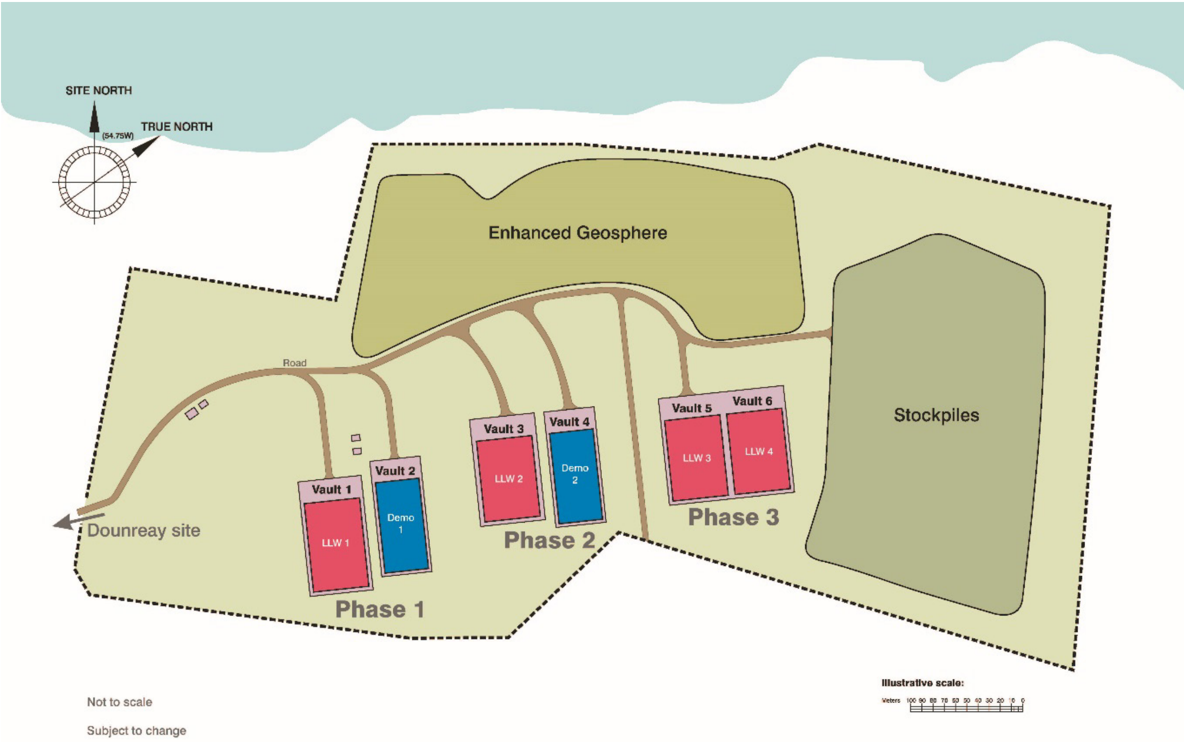

Figure 5.5: Layout for D3100, illustrating the existing features (Phase 1 vaults, enhanced geosphere and stockpiles) and a possible layout for Phases 2 and 3. However, the need for and order of future vault construction is under review. Note that the drawing is orientated to Dounreay site grid north being vertically upwards.

145 The vault dimensions are shown in Table 5.2. Note that the reference Run 5 PA calculations presented in Section 7 of this ESC assume the as-built vault dimensions given in Table 5.2. There are likely to be further changes in the estimates of waste volumes as the D3100 project proceeds. This is one of the main reasons for the strategy of phased construction. Phase 1 of the LLW and Demolition LLW vaults are built as stated, and the waste disposal volume offered by these vaults is considered to be the minimum needed. Phases 2 and 3 of vault development will be reviewed and revised as necessary to meet any changes in future waste arisings, and future decisions concerning waste management.

Table 5.2: Dimensions of the D3100 vaults ('as-built' for Phase 1 vaults and currently planned for Phases 2 and 3 [30, Tab.1, ¶60, ¶147]). Lengths are perpendicular to the coastline.

Parameter	'As-built' and Current Plans
LLW-1 vault internal length	79 m
LLW-1 vault internal volume	1,960 HHISO**
LLW-2 vault internal length	57 m
LLW-2 vault internal volume	1,360 HHISO
LLW-3 vault internal length	72 m
LLW-3 vault internal volume	Pair of vaults; 2x1,760 HHISO

Parameter	'As-built' and Current Plans
LLW vault internal width	49.5 m
LLW vault internal depth	11.1 m
LLW wall thickness	500 mm
LLW lid thickness	500 mm
Demolition LLW-1 vault internal length	78.5 m
Demolition LLW-1 internal volume	26,252 m^3
Demolition LLW-2 length	57 m
Demolition LLW-2 internal volume	19,062 m^3
Demolition LLW vault internal width	36.75 m †
Demolition LLW vault internal depth	9.1 m
Demolition LLW wall thickness	1,100 mm
Demolition LLW cap thickness	1,500 mm ‡

** Due to door design issues, the capacity of the LLW-1 vault is considered to be 1,960 HHISOs rather than the 1,968 that could theoretically be achieved with a different vault door design [155; 156, ¶67].

† The internal width is incorrectly cited in [30] as 39.75 m, but the correct dimension is 36.75 m.

‡ Demolition LLW cap thickness is specified in [173].

5.2.2 Depth

146 The depth of D3100 reflects a consideration of factors including radiological impacts from the groundwater pathway, probability and consequences of disruption, environmental impacts such as material use, drainage, visual impact, and construction nuisance, monitoring and cost. The considerations are summarised here and are described in more detail in the Stage 2 optimisation analyses [144, Ch.5; 147].

147 To support the Stage 1 BPEO study, UKAEA undertook an assessment (the Run 1 PA) of the radiological performance of an above-surface, shallow below-surface (10 m depth), and cavern (50 m depth) LLW disposal facility at Dounreay [157; 158]. All three facility types were shown to meet radiological performance targets. Calculated radiological performance in relation to the groundwater pathway did improve with increasing depth of facility (e.g. [7, Fig.9]), but only improving from an already-compliant level (risks $<10^{-6}$ per year). The main reason for improvement with depth is illustrated in Figure 5.6, which shows that, once the near-field engineering has degraded over the first hundreds or thousands of years after closure, releases from above-surface facilities have more potential to contaminate the soils between the facilities and the coast. Groundwater flows at depth are lower, and releases are more likely to migrate to the marine environment offshore, rather than to land. This consideration has been further assured by the introduction of the enhanced geosphere barrier on the ground surface between the vaults and the cliffs. However, because calculated doses are very low, the radiological impact from the groundwater pathway was not considered to be a strong distinguishing factor between alternative depths for D3100.

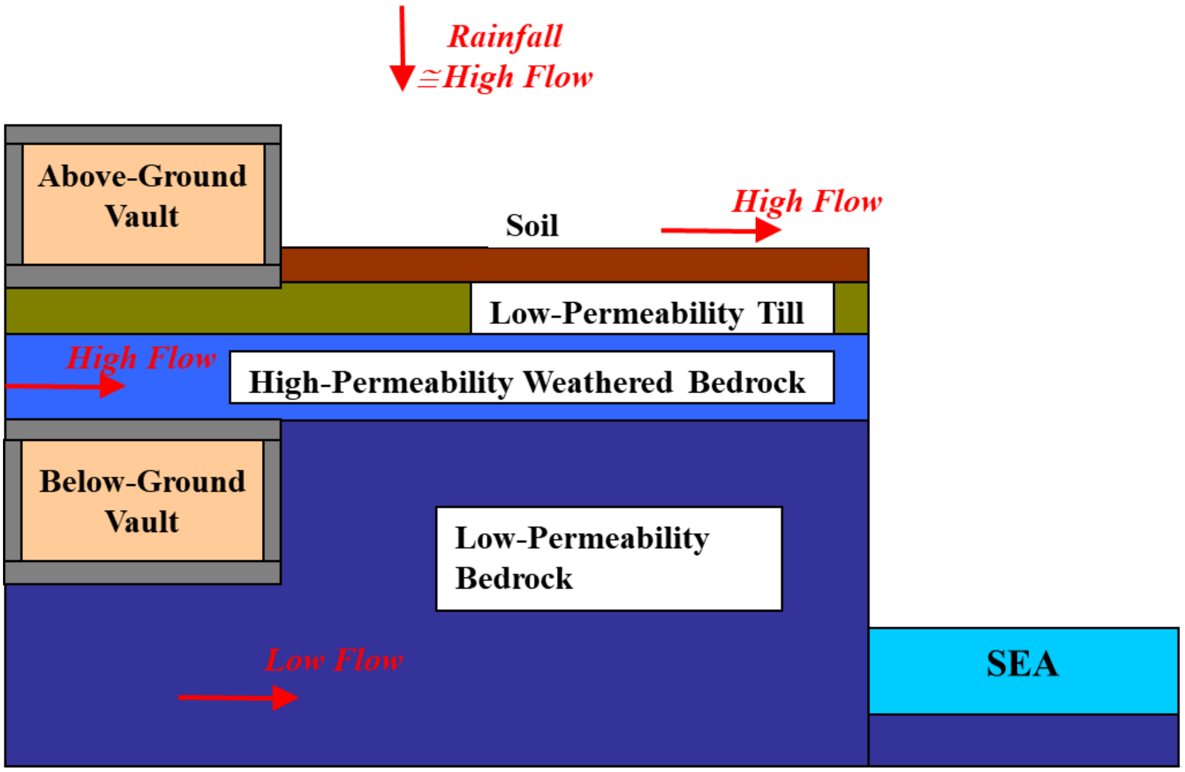

Figure 5.6: Illustration of water flows and flow paths (red arrows) from facilities located above-surface or below-surface at Dounreay. Figure drawn to support Stage 1 BPEO assessment and precedes introduction of the enhanced geosphere design. Schematic section runs from south (left) to north (right).

148 Both the probability and consequences of inadvertent intrusion and disruption decrease with depth of disposal. The probability decreases because the wastes are further from the human environment and surface-based activities and events. Facilities below the surface are less likely to be disrupted by natural events such as tsunamis or glaciation. Furthermore, a large artificial mound as would be created by the capping of above-surface facilities would be a prominent feature on the Dounreay coastal plain and could be seen as an obvious source of construction materials or be intruded through curiosity if awareness of the facilities had been lost in the far future. The consequences of inadvertent intrusion and disruption decrease with depth because intrusion of an above-surface facility is likely to involve direct disruption of more waste material, with greater associated risks, than for a below-surface facility (e.g. [157, Fig.A2.50]). The trend is not linear, with a sharp decrease in risk until a certain depth is reached, coincident with the maximum depth likely to be reached by most construction-related activities (assumed to be the most likely future use of the area after knowledge of the facilities has been lost in the far future). Once below the depth of construction activities, there is little further reduction in the risk of intrusion with increasing depth until beyond the range of simple drilling activities (i.e. hundreds of metres).

149 Below-surface facilities create a considerable volume of excavation material and associated non-radiological short-term environmental impacts compared to above-surface facilities. However, this excavated material can be used for

capping/facility closure. If above-surface facilities were constructed, then material would need to be imported for capping at closure. There would be a requirement to transport this imported material along local roads.

150 Throughout the planning and design of the facilities, the intent has been to operate D3100 "dry". This intent is more straightforward to achieve for above-surface facilities where, depending on the depth of foundations, groundwater inflow is low and water can be drained away by gravity. Below-surface facilities require pumping or more engineering to drain deeper groundwater. All facilities would need to be engineered to cater for accidental water ingress, but below-surface facilities present a lower profile compared to above-surface facilities and the roofing would be less vulnerable to extreme weather events.

151 Visual impact decreases significantly with depth, until the facility is entirely below the surface. Above-surface facilities present a potentially significant visual intrusion during construction, operation, and post-closure periods. Visual impact was identified as a sensitive issue in the EIA [16] and in consultation with local stakeholders.

152 Both above-surface and below-surface facilities present some noise and dust nuisance during facility construction, but below-surface construction may be worse owing to the need to excavate more rock. However, optimum excavation techniques and water management can be utilised to minimise dust creation, and receptors will be shielded from noise by the surrounding ground. During operations, below-surface facilities can be expected to have a lower degree of nuisance as the majority of activities will be below ground level.

153 Direct excavation costs increase with depth, significantly so for a cavern facility accessed via a shaft or tunnel. The cost of constructing and operating a cavern facility was assessed to be around twice that of the facility designs open to the surface [7, ¶117]. The difference in cost between above-surface and below-surface designs open to the surface was assessed to be marginal.

154 DSRL selected a below-surface design for the facilities, reflecting the benefits gained concerning radiological risks from human intrusion, visual impact, and material import compared to an above-surface design. There may be marginal disadvantages concerning construction noise and management of drainage during operations, but DSRL considered that these issues were insufficient to justify selection of an above-surface design. The design specified location of the wastes a minimum of 4 m below current ground level to place the wastes below the shallow weathered zone of potentially higher groundwater flows (see Section 6 and Figure 5.6) and at sufficient depth to be below the most likely intrusive activities. DSRL considers this to be the optimal depth. While a still deeper design may be marginally "safer" considering only risks from post-closure disruption, there was not considered to be a further advantage to be gained in going deeper, as costs increase significantly and worker risks associated with construction and operation of the facilities may also increase.

5.2.3 Waste conditioning and packaging

155 Waste treatment options were assessed in the Stage 1 BPEO study [7, App.1]. Waste segregation options, and alternatives to packaging and conditioning the wastes that do arise, have been reviewed by DSRL (e.g. [141; 144, Ch.7]).

156 The strategy at Dounreay set out in the planning application envisaged the grouting of LLW in mild steel containers that satisfied project requirements for on-site transport, stacking and monitoring. This was based on a Stage 2 BPM analysis that considered a qualitative balance between cost, acceptability, practicality, impact on radiological performance, and currently accepted practice [144, Ch.7]. Other possible packaging options considered in the analysis included concrete, stainless steel, paper-based materials, and no packaging. For LLW, the relatively high cost of stainless steel waste containers cannot be justified given that post-closure performance of the facilities is acceptable without taking credit for containment and that acceptable operational safety can be achieved using cheaper alternatives such as mild steel or concrete. Based on the long UK experience of using mild-steel containers for LLW disposal at LLWR, and because of the higher weight and lower waste-to-container volume ratio of concrete containers, the best practicable waste container material for Dounreay's LLW was selected in the analysis as mild steel [144, Tab.7.3] and mild-steel containers were assumed during the design of D3100. The potential to use concrete containers rather than mild steel HHISOs was revisited between 2012 and 2018 [159; 160]. Studies concluded, however, that benefits would be outweighed by disadvantages, and the option has not been taken any further forward.

157 Until recently (ca. 2018), the HHISO containers used for LLW disposal at D3100 have been the same design as those used at LLWR, namely the TC01 (2910C) Type IP-2 ISO Container. A change in operational requirements at LLWR, however, has led to a change in the design of the lid for the TC01 container which would render it incompatible with WRACS and the D2179 grout plant at Dounreay [161]. Therefore, a DC01 Container, based on the TC01 Container with the earlier Type C Lid, has been designed at Dounreay in response. The main difference between the containers is that the DC01 is not subject to registration as an IP-2 rated shipping container as there is no need to transport LLW on public roads or highways between the Dounreay site and D3100 [161] – this significantly reduces quality assurance (QA) burdens during manufacture, and thus reduces associated cost [160]. The DC01 containers are painted yellow in order to allow easy differentiation between these and the red TC01 containers [161]. An overview of the DC01 container design may be found in reference [161]. Figure 5.7 below shows stacked TC01 and DC01 HHISO containers.

Figure 5.7: TC01 (red) and DC01 (yellow) HHISOs stacked in the D3120 LLW vault in June 2020.

158 The containers are stacked in D3120. A stacking height of eight HHISO-type LLW containers has been selected in an optimisation analysis [145, ¶83-85], and this is illustrated in Figure 5.2. The eight-high stacks will be implemented in two layers, with the entire vault filled four-high before a new floor is created and the entrance ramp reprofiled; the second layer of four-high stacks will then be emplaced (see paragraph 167). The actual containers used for LLW may also include different sized containers in some cases. The emplacement of waste will be assessed on the basis of waste characterisation information to provide a reasonably homogeneous distribution of radioactivity in the facilities that conforms with the assumptions in the PA and with the operational safety requirements for the facilities [127]. To allow emplacement of containerised waste, the doors to the vaults have been designed to allow access for a standard articulated truck and trailer unit carrying two full-height ISO-type containers [145].

159 In addition to containerised waste, some large non-containerised items of LLW may be placed directly into the vaults and surrounded by grout *in situ*. However, a BPM analysis of the infrastructure and possible plant requirements associated with such emplacement (e.g. in-vault crane system, grouting and ventilation systems, and access arrangements) found that, unless there are significant difficulties associated with size reducing items, there is likely to be a cost benefit from size reduction and minimisation of waste volumes [145, App.3]. Therefore, no special provisions are currently proposed for the handling and consignment of non-containerised waste in

the LLW vaults, although preliminary WA Rules for non-containerised waste have been developed [54]. A case-by-case BPM assessment of the merits of non-containerised waste emplacement versus size reduction and packaging will be required to facilitate disposal. Each assessment will have to consider issues such as containment of the waste item during transportation, emplacement and grouting, worker dose assessment both at the originating plant and in the vault, and the practicalities of size reduction.

FP.5 As necessary, develop guidelines for BPM assessment for the acceptance and emplacement of non-containerised waste.

160 From emplacement until closure, access for inspection and monitoring of the emplaced LLW packages can be made available on the operational face of the vault and across the top of the emplaced containers [139, ¶116].

161 As noted above, cementitious grout has been chosen as the BPM for LLW conditioning [144, ¶202]. The grouting provides short-term shielding and stability during the operational period, and also has long-term performance benefits. Cementitious grout is preferred as a conditioning medium, compared to alternatives such as bitumen or polymers, as:

- it displays favourable long-term chemical and mechanical stability, high strength and low permeability;
- it promotes a stable chemical environment that reduces the mobility of key radionuclides;
- it can be emplaced by means of familiar technology, and its physical and chemical properties are generally well understood; and
- the raw materials are readily available and relatively inexpensive.

162 Grouting of waste within HHISOs is undertaken at the D2179 grout encapsulation plant on the licensed site. The composition of grout is specified to best meet the performance benefits set out above, and it is sufficiently fluid to fill the accessible voidage in the wasteform [162]. Inaccessible voidage is minimised to promote low permeability and stability. At the encapsulation plant, the grout port lid of each HHISO is removed to allow grout to be added. Each HHISO is left for 16 hours for initial grout curing, and then a secondary grout pour is undertaken to ensure the gap at the top of the containers (the ullage) is reduced as much as is reasonably practicable [163, ¶112]. Further top-ups are undertaken if ullage is still greater than 20 mm prior to transfer to the LLW vault.

163 Stage 1 of the D3100 project identified disposal of the Demolition LLW in simple engineered vaults separate to the remainder of the LLW as the BPEO [7]. This is consistent with national LLW policy [3] and the GRA [19] in taking account of the low hazard presented by the waste compared to the remainder of the LLW streams to develop a proportionate and discrete management strategy. Packaging and handling arrangements for Demolition LLW have been evaluated through a BPM analysis [145, App.2], which considered waste loose or grouted in HHISOs, waste in polypropylene bags emplaced in layers or terraces, loose waste placed directly in the vaults, and

cemented waste blocks emplaced either *in situ* or by forklift. The BPM analysis identified the highest scoring option, by a narrow margin, to be loose emplacement of Demolition LLW within the vaults. However, all of the options were closely ranked. Cost considerations support loose or bagged emplacement. However, operational control, and visual appearance and perception considerations led the project team to conclude that the favoured option is the emplacement of bagged waste in layers with a fine-grained loose backfill material. For comparison, the emplacement of bagged waste in layers with a sand fill system is currently in use at the Morvilliers disposal facility for very low-level radioactive waste in France (e.g. [164]). Figure 5.8 shows bagged Demolition LLW emplaced in the D3130 vault being backfilled with sand.

Figure 5.8: Bagged Demolition LLW emplaced in the D3130 vault.

164 A programme of work is ongoing to optimise the extant waste emplacement strategy for Demolition LLW. This programme of work is seeking to improve packing efficiency in the Demolition LLW D3130 vault to ensure optimal use of vault space and also to minimise post-closure settlement. The work is considering emplacement methods of the standard Demolition LLW bags and also different sizes and shapes of waste package. Off-site trials have been undertaken to assess a 360° tracked excavator using different attachments to pull and press the waste packages to achieve better placement and compaction of waste, without compromising package integrity [165]. These trials were considered successful and further trials were subsequently undertaken in the D3130 vault to inform the ongoing optimisation of waste emplacement [166].

5.2.4 Backfill within the vaults

165 The primary function of the backfill material used within the vaults[21] is to enhance the engineered performance of the facilities. The choice of vault backfill material affects the porosity of the vaults (by filling of voids inside the vaults), waste stability within the vaults, and both physical and chemical radionuclide retardation after closure. The options that have been considered for vault backfill include high-permeability materials, cementitious materials, and bentonite-based materials.

166 A grout backfill around the LLW packages has been selected to create a low-permeability block-like structure in the LLW vaults [144, Ch.7]. A cementitious backfill will be compatible with the cementitious grout selected as the encapsulant for the LLW packages. In its fluid form, the backfill will be straightforward to emplace into the narrow gaps [167]. The interstitial grout, in conjunction with the HHISO container corner posts provides structural support for the vault lid and cap [168]. The grouted waste and backfill will be composed of the same material and can be expected to exhibit the same behaviour with regard to gas migration. As necessary, non-containerised items will be backfilled *in situ*.

167 The extant plan is to backfill the LLW vaults in two stages, first when HHISOs have been stacked four-high throughout the vault, creating a new floor and reprofiling the entrance ramp, and then secondly when the vault is full. However, a recent options assessment [169] concluded that rather than undertaking two large interstitial grouting campaigns, the grouting should be undertaken in a number of smaller, more regular, campaigns in order to reduce the technical and practical risks associated with the task. DSRL is currently finalising documentation ahead of a submission to SEPA for approval to undertake the first phase of such work in the LLW vault, which is expected to commence in early 2021 [170]. However, a new floor will still be created and the entrance ramp reprofiled once the entire vault is filled with HHISOs stacked four-high, before vault emplacement and periodic backfilling operations commence again.

168 There will be no cement grout backfill used within the Demolition LLW. However, a thin layer of granular material (e.g. sand) is used to infill voids around the Demolition LLW within the vaults to minimise settlement of the waste and to give safe operational access over the top of already-emplaced waste. The lid on the Demolition LLW vaults will not be a stiff material, and will be designed to accommodate the settlement of the waste and backfill matrix over time.

169 The off-site trials for optimisation of Demolition LLW emplacement [165] also assessed the effectiveness of different granular materials for use as a backfill and running surface. A combination of sharp sand (natural aggregate as defined in BS13139:2002) and crushed Type 1 (as defined in the Specification for Highway works, clause 803 and Standard BSEN 13242) were tested. Type 1 provides a more effective backfill and running surface, with sand providing a better surface dressing

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21 Some references use the term "infill" and "backfill" variably for material placed around waste packages in the vaults and material placed externally around the vault walls. The term "backfill" and the process of "backfilling" has been used for both situations here, but with a clear distinction being made as to whether the interior or exterior of the vaults is being discussed.

that minimises damage to packages during emplacement. The effectiveness of different combinations of these materials is being assessed in order to inform the ongoing optimisation of waste emplacement [171].

5.2.5 Base and walls

170 Alternative engineering has been reviewed by DSRL, including review of similar facilities worldwide and international guidance [136; 141; 142]. The advantages and disadvantages of each of the primary construction materials, in the context of a highly-durable, low-maintenance, performance-assured facility design, have been examined [144, Ch.7], together with prospects for the development of material technology and advances in design.

171 The vaults have been constructed with a reinforced concrete base and walls, with a steel portal frame and roof for the operational period. The roof has sufficient internal height to provide handling clearance and enable grouting and concreting activities.

172 An external waterproof membrane was considered in the Stage 1 design [143, Fig.2.3]. It was envisaged that, in the absence of access for maintenance, a membrane may not be appropriate over the timescale under consideration. Instead, it is considered that the specification for the hydraulic performance of the walls of the vaults, in association with the grout and container matrix and engineered cap will address the long-term challenge of water ingress into the vaults and keep the waste dry for as long as practicable. The D3100 EASR Permit requires that the vault base, sides and final cap consist of an artificial engineered barrier that ensures a permeability of at least 10^{-9} m s^{-1} and where the barrier thickness is not less than 0.5 m [14, ¶7.4].

5.2.6 Drainage

173 During operations, a metal roof prevents rainwater from entering the concrete vaults and the drainage system, in the form of channels around the facilities to pumps, diverts groundwater and surface water flow away from the excavations to discharge points in the enhanced geosphere. The risk of flooding has been minimised through the adoption of a split-level drainage system: an upper gravity system carries the more variable surface water and shallow groundwater flows in open channels, and a lower mechanical pumped system carries the more constant deeper groundwater flows. As discussed in Section 6.2.4, pumping has created a groundwater depression cone around the vaults, elongated along the hydraulic gradient (towards the coast). Analysis of groundwater monitoring data has led to the suggestion that the groundwater system near the excavation is one where the water table is drawn down to the elevation of the excavation sumps.

174 The drainage volumes and pumped water quality are monitored. A response strategy for failure of the drainage system has been included in the design development. The lower system includes attenuation, redundancy and duplication (e.g. back-up pumps) and controls. Separation of the LLW and Demolition LLW vault excavations with independent pump systems has been adopted to prevent possible mixing of floodwater between the vaults in a hypothetical extreme storm event. Flood barriers

have been installed at the vault entrances to further minimise the risk of floodwater entering the vaults.

175 As waste emplacement proceeds, the open area around the external vault walls will be backfilled to provide structural support (Figure 5.2). There are two main options for the choice of drainage backfill, either high-permeability or low-permeability material. Neither option would compromise the performance of D3100. However, the use of a high-permeability material will reduce long-term disruption to groundwater flow in the area and reduce the likelihood of a downstream low-permeability barrier forcing groundwater upwards in the long-term, which would be detrimental to radiological performance. Further, the material for a low-permeability barrier would need to be imported, creating local impacts, while there is the potential for some of the high-permeability backfill to come from rock in the stockpiles formed during the excavation of the vaults (see Figure 5.5). Therefore, a high-permeability backfill of excavated rock has been selected as the optimal solution to take forward [147]. A high-permeability backfill around the external walls of the vaults will create a “hydraulic cage” effect on the groundwater flow pattern, effectively diverting groundwater around the vaults rather than into the vaults. The design of the cap has considered the potential for upward flows from the backfilled zone around the vaults into the near-surface groundwater and the clay lid covering the vaults (see below) will be extended over the backfilled zone to prevent any such flows.

176 Backfill to approximately floor slab level of the open drains around the Phase 1 vaults was undertaken in 2018 in order to provide a stable working surface during essential maintenance operations to replace the bird meshing between the walls and roof of each vault [172]. Further backfilling in parallel with the multi-stage approach to interstitial grouting is proposed in the near future.

5.2.7 Lid and cap

177 At closure of the facilities, a lid will be placed on each vault, the roof removed, and an engineered cap installed over the lid. The lid over the LLW vaults is likely to differ from the lid over the Demolition LLW vaults to allow for differing rates and degrees of settlement. Separate excavations for the Demolition LLW and LLW vaults will allow the systems to act independently. Clay materials are more ductile than concrete, and a clay lid will more readily accommodate settlement of the waste during the closure period [145, App.4]. The current design therefore envisages a thick clay lid over the Demolition LLW vaults and a concrete lid with a thinner overlying clay layer over the LLW vaults.

178 BPM analysis has been undertaken for the design of the cap [144; 147] and a scheme design developed [173], although the detailed design will only be finalised at the time of closure. The design is in accordance with international best practice [174]. Above the lid described in the previous paragraph, the cap is engineered to minimise disruption to the near-surface higher-flow groundwater zone above the waste vaults. The cap also includes an anti-intrusion layer, which is expected to be formed with large slabs of excavated rock. The thickness of the cap over the vaults will be varied to return the area to a profile that will be blended in with the local topography. Considerable experience exists in the installation of caps over waste disposal

facilities, providing confidence that the closure design of D3100 can be implemented to meet requirements.

5.2.8 Enhanced geosphere

179 Enhancing the geosphere by landscaping the area between the vaults and the coast using a layer of excavated rock [175] acts to reduce calculated radiological risks in the long term after closure (see Section 7). Construction of the enhanced geosphere will result in an elevation of the soil zone, and in so doing will effectively lower the water table following closure of the facilities, thereby reducing the potential for upward flow of groundwater to the new land surface. There was no additional cost to developing this enhancement, as the physical works in landscaping the area and developing the enhanced geosphere were similar to those that would be incurred anyway for earthworks and storing excavated material. There were no significant disadvantages to the option of enhancing the geosphere. The enhanced geosphere layer will be keyed into the cap over the disposal vaults as shown schematically in Figure 5.9.

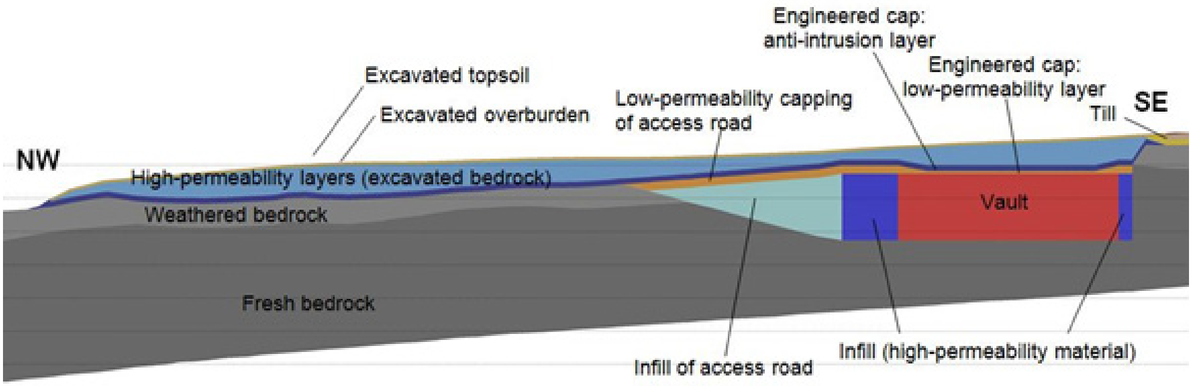

Figure 5.9: Illustrative cross-section of the main (hydro)geological features of the disposal facilities, the geosphere and the enhanced geosphere. Adapted from [176].

5.2.9 Impact of engineering on the geosphere

180 The choice of cementitious materials for the wasteform, backfill and barriers is based on best practice, availability and understanding of the behaviour and performance of grout and concrete. The use of the same materials throughout the facilities ensures internal compatibility. The main impact on the geosphere will be the migration of alkaline pore fluids into the rock and groundwater surrounding the facilities while the cements and concrete degrade over time. Given the carbonate-rich nature of the Dounreay groundwaters, this migration is likely to be reflected in a transient phase of precipitation of calcite and calcium-silicate-hydrate (CSH) phases in fractures [177, ¶45]. Based on modelling and analogue studies for other cementitious waste disposal systems, the extent of the zone of alteration is uncertain, but is unlikely to be extensive [177, ¶48]. There may even be a decrease in the hydraulic conductivity of the geosphere associated with the alteration, although evidence from natural analogues and modelling studies is not conclusive [177, ¶48]. Calcite is already a

common phase in the bedrock and the use of cement in D3100 is compatible with the host rock conditions. Therefore, the potential effects of the alteration can be readily covered in the PA as part of the uncertainty analysis for the natural variation in sorption and hydrogeological conditions in the geosphere (Section 7).

5.2.10 Design and gas generation

181 Owing to the nature of the Dounreay LLW, being predominantly composed of metals and concrete (see Table 4.4), only small volumes of gas generated from decomposition of the wastes are anticipated following closure [177, Ch.7]. Cellulosic material comprises only a small proportion of the inventory. Under aerobic conditions, decomposition of cellulose will yield carbon dioxide, but this is likely to react with the cement in the wasteform and not migrate (e.g. [178]). Reaction of carbon dioxide with cement will lower the retardation potential. However, the small volumes of gas are unlikely to create a major problem in this regard. A separate gas phase is only likely to be created under anaerobic conditions, through generation of methane from anaerobic decomposition of cellulosic material and hydrogen from anaerobic corrosion of iron and steel.

182 Anaerobic conditions are expected to be created in the LLW vaults rapidly once water infiltrates the waste after closure and corrosion and degradation reactions progress. As a bounding case, DSRL has estimated maximum gas generation rates assuming anaerobic conditions throughout the repository at closure [177, Ch.7]. Assuming an initial gas permeability of 10^{-16} m^2 for the cement wasteform and backfill, and a maximum gas generation rate of 30,000 m^3 (STP) per year from cellulose degradation and corrosion [177, ¶234] (generation rates are actually expected to be much lower), a pressure gradient of around only 0.1 MPa (1 atmosphere) would be required for the gas to migrate out of the facilities. This pressure gradient can be accommodated by the concrete vault structures and, therefore, it is reasonable to assume that any gas generated will be released with minimal disruption or effect on fluid flow. The LLW containers are not designed to be gas-tight (in fact, the grout port is left “rattle fit”) and will not significantly impede gas flow as they degrade in the first few tens to hundreds of years after closure [179]. There may be some pressurisation from gas build-up beneath the cap/lid. However, gas generation will be spread over hundreds of years, and there will be an increase in cap/lid permeability over this timescale that will facilitate gas release with minimal disruption. A gas modelling study for the Demolition LLW vault [180] confirms that if water is able to find a pathway for ingress into the vault to saturate the waste to generate methane gas, then that same pathway will provide a means for the generated gas to be released from the vault.

5.2.11 Design and hazard containment

183 Only a few non-radiological hazardous contaminants, mainly lead, copper and asbestos, are anticipated to be present in the LLW in any significant quantity (see Table 4.5), and these contaminants are present in inert forms or will be rendered inert by the waste conditioning. The high-quality engineering of the vaults, the waste conditioning and packaging, and the cementitious backfilling planned for D3100 provide for long-term containment of the hazardous materials, and are considered by

DSRL to represent the best available techniques [181; 53]. The engineering has been specified such that it meets the landfill regulations for a hazardous waste facility, with floors and walls made from concrete with a hydraulic conductivity of $\leq 1 \times 10^{-10}$ m s^{-1} and ≥ 0.5 m thick. Therefore, a suitable level of long-term protection of the water environment and flora and fauna, including humans, against non-radiological hazards will be provided by D3100 [181; 53]; this is discussed in more detail in Section 7.10.

5.2.12 Design and criticality

184 Section 7.11 discusses development of the criticality safety case and the fissile mass limits in the WA Rules that ensure that criticality is not a concern in D3100. Therefore, no specific further requirements have been included in the design to address criticality safety, although, as a precautionary measure and in order to provide further assurance that criticality after closure is not credible, the D3100 load management plan [127] includes a requirement to ensure that HHISOs with higher fissile content are spread evenly, as far as practicable, throughout the vaults.

5.2.13 Design and temperature

185 The small temperature rise from curing of the grout during waste conditioning will have largely dissipated before the waste is transported to the vaults. Possible temperature rises in the vaults as a result of radioactive decay and microbial activity were reviewed in [177, ¶ 257], where it was concluded that the temperatures are not likely to rise significantly above ambient. Temperatures in similar facilities are around 10°C [177, ¶258]. Therefore, as Dounreay is located in a temperate climate, no specific measures have been included in the design of the facilities to manage heat generation.

5.2.14 Design and retrievability

186 During Stage 1 of the D3100 project, the potential advantages and disadvantages of designing different degrees of retrievability (i.e. the ability to reverse the actions of waste emplacement) into a LLW disposal facility were considered [182]. After reviewing the published literature on approaches to retrievability in other waste disposal programmes, stakeholder perceptions and opinions in the UK and abroad, and UK regulatory policy, a workshop was held at Dounreay to examine the views of a group of local stakeholders regarding the concept of retrievability and its role in the management of LLW.

187 The retrievability workshop participants considered that, rather than focusing on retrievability, it would be more appropriate to emphasise that the waste management decisions are being made by experts to assure that the most appropriate actions are taken, and that confidence in the successful management of the waste is high [182, App.1].

188 Stakeholder responses to public consultation on radioactive waste management for higher activity wastes included a wide range of views on the benefits and detriments of retrievability, including a view from the Environment Agency that "*we will not accept a safety case that invokes retrievability as a significant contributor to the case. This*

in our view would place undue burdens on future generations (as well as substantially increasing the uncertainties associated with the case)" [183]. This position is now emphasised in the GRA [19, ¶3.6.2 and 3.6.3], where it is stated that the guidance "*does not require the waste to be retrievable after the act of disposal i.e. emplacement of the waste*" and "*if a developer/operator makes provisions for retrievability, these should not unacceptably affect the environmental safety case*".

189 In conclusion, in accordance with the GRA and with the findings of the Dounreay retrievability workshop and indications of stakeholder views in the UK on waste retrievability, this ESC is for waste disposal without either the intent to retrieve the waste or the implementation of specific provisions that might ease waste retrieval. Thus, the disposal approach for LLW consists of the following sequential steps: the wastes will be size-reduced as appropriate, conditioned and packaged into a form suitable for final disposal, the conditioned and packaged wastes will be emplaced in the facilities, the facilities will be backfilled, and finally the facilities will be capped and closed after the cessation of disposal operations. The approach for Demolition LLW is similar, except without the conditioning, and with less robust packaging given the much lower intrinsic hazard. This approach is the most cost-effective, minimises operational problems, and is an appropriate long-term solution [182, ¶79]. Despite this approach, waste retrieval is still possible if considered necessary, though with an increase in difficulty after backfilling, and yet further difficulty increasing with time after final capping and closure. Even after closure, retrieval of wastes from the D3100 would likely be more straightforward than a number of the other tasks currently being pursued in the Dounreay decommissioning programme (e.g. retrieval of wastes from the Shaft and decommissioning of the Dounreay Fast Reactor). An intervention strategy to potentially retrieve disposed of waste is a requirement of the EASR 18 Permit [14, Condition 9.3], and is included in the OMP [116].

5.3 Construction of D3100

GRA 6.4.19	Show that the methods of construction of the facility are consistent with the claims made in the environmental safety case, in that they do not unduly disturb the geological environment and the containment properties of the host rock.
GRA 6.4.25	For facilities that are not regulated under the landfill regulations and not owned by a public sector body such as NDA, ensure that suitable financial provision has been and is being made such that the obligations (including any aftercare obligations) arising from the authorisation are being and will continue to be fulfilled.
GRA 6.4.32	Make plans for corrective action to deal with foreseeable geological or geotechnical problems which might arise during construction, operation or closure.

190 Construction is phased to enable the development and sizing of future vaults to be tailored with actual waste arisings. A possible programme of construction could be as follows, although the dates are dependent on the progress of decommissioning and will alter as the decommissioning programme evolves:

- Phase 1 construction was completed in 2014.

- Phase 2 may be constructed sometime between 2022 and 2026 (requirement tied with the decision to remediate the legacy LLW Pits).
- Phase 3 construction timescales are dependent on decommissioning waste arisings.

191 Construction includes the provision of infrastructure (access roads, services, fencing and drainage). Construction activities are specified and conducted in such a manner so as to minimise impacts from construction, as set out in the mitigation measures specified in the Environmental Statement [16].

192 As required by the D3100 EASR Permit [14, ¶7.5] and by good practice, construction activities have been, and will be, undertaken within a Construction Quality Assurance (CQA) scheme, to ensure that the facilities meet the requirements set out for the build. The Design and Build Contract Specification for Phase 1 included the use of a CQA scheme and DSRL engaged an independent CQA consultant to undertake an audit and monitoring role to ensure that the construction of the concrete vault base and walls was satisfactory and to allow verification of other performance requirements (i.e. concrete thickness) [184].

193 Construction of the Phase 1 vaults was undertaken by Graham Construction and was timed to allow for near continuous working – whilst sections of floor/wall in one vault cured, work was undertaken in the other vault [150, §6.6]. Construction went generally to plan, although some modifications were required:

- Following construction, cracks were identified in the concrete walls of the vaults. Some cracking is expected during concrete curing, but greater cracking than expected was observed in the Demolition LLW vault walls. A BPM study for the Demolition LLW vault was undertaken to manage these cracks to satisfy the design intent of low-permeability vault walls (hydraulic conductivity of $\leq 1 \times 10^{-10}$ m s^{-1}). The preferred remedial option was to use surface-applied cementitious coatings to fill the cracks on both the external and internal surfaces of the vault walls [185]. Figure 5.10 shows the polymer-modified cementitious coating used on the east wall of the Demolition LLW vault. The cracks in the LLW vault did not challenge the design intent, but were patched at the same time as the cracks in the Demolition LLW vault anyway [186].
- During the Phase 1 construction period, the original designs of the steel vault roofs were optimised considering whole lifecycle costs. The spacings between portal frames of each roof were increased, requiring fewer bays while maintaining the specified structural withstands [149, ¶123]. In addition, the roof pitch was increased for both vaults to optimise steel usage [187]. However, as the roof was included predominantly for operational purposes and there are no post-closure safety assumptions related to it, these design changes did not impact the assumptions that underpin this ESC.

Figure 5.10: The applied polymer-modified and reinforced cementitious coating applied to cracks on the internal walls of the Demolition LLW vault [188, p.5].

194 Site characterisation has been, and will continue to be, undertaken to show that the characteristics of each part of the site meet any pre-defined requirements (see Section 6). Requirements might include geotechnical specifications, such as minimum acceptable rock strength and maximum acceptable water flows, location with respect to faulting, and consistency with PA assumptions. The requirements and procedures to undertake characterisation during construction, evaluate data against requirements, and identify corrective actions as necessary will continue to be developed on the basis of design, PA and site characterisation needs before any future construction starts.

5.4 Operation and Closure of D3100

195 The operations in the vaults primarily involve the checking and acceptance of packaged and conditioned waste from the Dounreay site, and the placing of waste in the vaults. Operations and associated design requirements for the scheme design were initially described in the Design Justification Report [139] and a preliminary operational plan [189]. The Phase 1 LLW and Demolition LLW vaults are operated according to the OMP [116].

196 Operations are, and will continue to be, conducted in a manner that does not impact on the long-term performance requirements of the engineering. Procedures for routine inspection and cyclic maintenance have been developed as necessary, although the D3100 facilities are relatively simple to maintain. The concrete vault structure is highly durable, inherently robust and stable. The structural steelwork was built with a design life of 25 years, but there is evidence of premature failure of the

protective coating on the steelwork in both vaults (the protective coating specification expected no maintenance for the first 15 years). DSRL are reviewing options for managing this failure in light of the extended operational life of the vault as now envisaged [150, §7.4]. Arrangements for maintenance of D3100, including inspection, testing and maintenance of vehicles, water pumps, sumps, ventilation equipment, and fire safety equipment, is set out in the DSRL Mainsaver system [116, ¶117].

197 As discussed in Section 5.2, during operations regular grouting campaigns will be undertaken in the D3120 LLW vault to backfill around the HHISO containers, with associated void filling of high-permeability material around the exterior of the vault to balance the loads across the vault walls. The eight-high stacks of HHISOs will be implemented in two major layers, with the entire vault stacked four-high before a new floor is created and the entrance ramp reprofiled; the second layer of four-high stacks will then be emplaced. Similarly, the D3130 Demolition LLW vault is backfilled was granular material as the waste is emplaced.

198 Closure of the vaults will involve sealing of all voids in the external walls, completion of any remaining backfill around the external walls, construction of lids over the vaults, removal of the steel roof and cladding, disablement of the operational drainage system, the installation of the engineered cap, reinstatement of the general area, and instigation of the post-closure monitoring programme. The majority of the closure activities are expected to have a positive impact on radionuclide retention within D3100, thus reducing radiological risk to the public after the period of authorisation [148]. The detailed design of the closure works to be undertaken some years hence is deferred until nearer the time of implementation, although it has been specified during the design-and-build work in Stage 3 of the D3100 project to the detail necessary to ensure that implementation will not be impacted adversely by the construction work. Currently, it is envisaged that as much of the excavated material as possible is to be used in backfilling around the vaults and for forming the engineered cap over the vaults. The adoption of a relatively straightforward roof construction will simplify the access requirements for removal and dismantling at closure and will avoid reliance on plant access over the vaults at the time of roof removal.

199 In accordance with the GRA [19, ¶6.4.25], no specific provision is made for setting aside funding to complete the closure of the facilities. Funding for the D3100 facilities is supplied by the UK Government through the NDA. The current UK Government approach for existing liabilities is to fund decommissioning activities, including waste disposal, from resource in the year in which the activities are undertaken (i.e. no separate pot of money is set aside to fund future LLW disposal commitments at Dounreay).

5.5 Design and Optimisation

GRA 6.3.56	**Requirement R8: Optimisation.** The choice of waste acceptance criteria, how the selected site is used and the design, construction, operation, closure and post-closure management of the disposal facility should ensure that radiological risks to members of the public, both during the period of authorisation and afterwards, are as low as reasonably achievable (ALARA), taking into account economic and societal factors.
GRA 6.3.59	To succeed, optimisation requires good communication, both within the developer/operator's own organisation and with supplier organisations, as well as with the regulators and the local community.
GRA 6.3.60	Where there are choices to be made among significantly different alternatives, carry out options studies. Present the results to the regulators and make them publicly available.
GRA 6.3.62	Optimisation needs to be considered at each decision-making stage. Once a decision has been implemented, it forms part of the framework within which further decisions, and the optimisation considerations that go with them, must be made. Even when a decision has apparently been made, it continues to represent an uncertainty before it has been implemented. The end of the period of authorisation is the end of decision-making by the developer/operator.
GRA 6.3.64	In the presence of uncertainties, make sure that an acceptable situation will result, not only in likely future circumstances, but also in circumstances that are possible but unlikely. Acceptability can be measured in terms of radiation dose or risk, but it will often be unnecessary to go as far as calculating these quantities to recognise a situation as unacceptable.
GRA 6.3.65	Once the main optimisation task has been fulfilled, follow the more usual path of finding the best way forward for each set of circumstances. At this stage, focus mainly on the likely circumstances. Unlikely circumstances should not have undue influence on design, construction or operation.
GRA 6.3.66	Favour a simple approach to optimisation rather than a more complex one, where either would deliver an adequate outcome. If a numerical approach is used to compare options, recognise that the size of the population at risk is a relevant issue as well as the magnitude of individual risks.
GRA 6.3.67	At each decision-making stage, provide a written record of the consideration of optimisation. As part of the environmental safety case, provide a historical record of the decisions taken and implemented, and the optimisation considerations that related to those decisions when they were taken.
GRA 6.4.4	Optimisation only applies to radiological risks, but adequate protection against non-radiological hazards needs to be maintained when optimising for radiological risks.
GRA 7.3.34	Demonstrate in the environmental safety case that optimisation considerations have been applied in all relevant decisions and at all relevant steps. Relevant steps include the choice of waste acceptance criteria, how the selected site is used and the design, construction, operation, closure and post-closure management of the disposal facility.

GRA 6.2.28	Before the decision is made to use a novel technology, carry out trials to demonstrate that any uncertainties about the outcome of using the technology are kept to a minimum.
GRA 6.3.45	Consider, and implement, any practical measures that might reduce the likelihood of human intrusion. Such measures should not compromise the environmental safety performance of the disposal system if human intrusion does not occur. The measures to reduce the likelihood of human intrusion should be considered as part of option studies under Requirement R8, Optimisation.
GRA 6.3.51	Use the results from human intrusion scenarios as part of option studies under Requirement R8, Optimisation to reduce the radiological impacts resulting from human intrusion, subject to balancing all the other considerations relevant to optimisation.

200 Optimisation of the management of Dounreay LLW is needed to satisfy both a principle and a general requirement in the GRA [19]. Optimisation requires that radiological risks to members of the public are ALARA during the period of authorisation and afterwards. However, the best way forward is not necessarily the one that offers the lowest radiological risk - optimisation is about finding the best way forward where many different considerations need to be balanced. Relevant considerations are listed in the GRA [19, ¶4.4.7] and include:

- the number of people (workers and the public) and other environmental targets that may be exposed to radiological risk;
- the chance they could be exposed to radiation, where exposure is not certain to happen;
- the magnitude and distribution in time and space of radiation doses that they will or could receive;
- nuclear security and safeguards requirements;
- issues similar to those above, but relating to non-radiological hazards;
- economic, societal and environmental factors; and
- uncertainties in any of the above.

201 Optimisation is considered at all stages in the lifecycle of the D3100 project and involves all aspects of the project. It involves continually questioning whether everything reasonable has been done to reduce radiological risks. DSRL is committed to optimisation and each decision in the development of D3100 has considered keeping the radiological risks ALARA. Although optimisation applies across the D3100 project, the discussion on optimisation is included in this section as many of the optimised decisions are covered here, with optimisation having been a central focus of the BPM analyses that have been conducted to date to support design decisions. This is exemplified by discussions in previous sections on optimisation of disposal facility siting early in the D3100 project through to more recent optimisation of the vault backfilling process. It is considered that the current design as presented here is optimised against the assumptions and current knowledge as set out in this ESC. However, these assumptions may change through developments external to the D3100 project and during future review and design

studies. Therefore, BPM/optimisation studies will continue to be undertaken as further decisions are taken during design, construction, operation, closure and post-closure management of the phases of the facilities.

202 The decision on the long-term management strategy for Dounreay's LLW was supported by a BPEO study [7] that compared and consulted on the different strategic options. The strategy chosen is considered to represent the optimised solution for the long-term management of Dounreay's LLW. The scope of the BPEO study was limited to LLW; further optimisation analysis has reviewed the inventory, and given the nature of the wastes at Dounreay, the planning framework, and stakeholder opinions, the limitation to LLW is considered to be the optimised solution [51].

203 The BPEO study in Stage 1 of the Dounreay LLW management project based the initial facility designs on international good practice [141]. Design options were analysed in terms of their implications on the safety assessment results (e.g. [157, ¶71]). In Stage 2 and Stage 3, BPM/optimisation assessment continued to be undertaken in a formalised and iterative manner, consistent with DSRL BPM procedures and regulatory guidance [103]. The Stage 2 and Stage 3 BPM/optimisation analyses covered a wide range of issues, including those listed in paragraph 200, tailored according to the options under analysis. The opinions of relevant stakeholders, collected as part of consultation on the planning application and in regular meetings with local stakeholders, have been taken into account. BPM studies have continued to be undertaken since the start of operations [51], and the current design is considered to represent the optimised solution. A summary of the BPM/optimisation analyses to date has been provided in this section and is outlined in Table 5.3.

204 The contents of D3100 represent a low hazard, and DSRL considers that the current design represents a proportionate solution for the management of the wastes. The engineering ensures waste containment for many decades after emplacement. The location of the vaults ensures that the short-term impacts to near-neighbours from construction and operation are as low as possible given the need to protect the facilities from future coastal erosion and sea-level rise. Measures to reduce the likelihood of inadvertent future human intrusion, such as placing the vaults underground and installing a thick cap, have been considered and included. Further measures, such as developing an underground facility some tens of metres deeper, have been discounted as disproportionate to the potential reduction in long-term risks, given the extra costs and non-radiological short-term environmental impacts and construction risks that would be involved. DSRL's safety strategy generally advocates use of established technologies and sound science and, while novel technologies have been reviewed and considered in the BPM/optimisation analyses, none have been selected in the design presented here.

205 As development and operation of D3100 progresses, optimisation work will continue to be undertaken as necessary. The 2020 optimisation summary report [51] will be updated in light of such work and the summary will continue to form a key supporting reference to the ESC (see Figure 2.4). Activities already identified for future studies are indicated in the right-hand column of Table 5.3. The BPEO report and the BPM/optimisation reports to date have been supplied to SEPA as a basis for dialogue on the decisions taken. This will continue. As was agreed during the planning

application, decisions will be discussed with local stakeholders during regular meetings held to update them on the developing project.

FP.6 Future design considerations and optimisation analyses.

Table 5.3: Areas of BPEO/BPM and optimisation assessments undertaken during the D3100 project – references are identified in the heading rows for further information [51, Tab.1.1].

Design Area	BPEO 2004 [7; 143]	BPM 2006 [144]	BPM 2007 [145]	BPM 2008 [146]	Optimisation 2010 [147]	Optimisation 2011 [148]	Optimisation 2014 [149]	Optimisation 2020 [51]	Planned Studies
Strategy	All management options	N/A							
Facility Type	A wide range of disposal and storage options	Disposal options – deep cavern, below-surface vaults, above-surface vaults							
Facility Location	A range of options, screened to exclude non-UK locations	Restricted to NDA-owned land at Dounreay		Site selection review taking account of site characterisation and geophysical survey	Borehole monitoring and local-scale hydrogeological modelling	Vault layout review			Refinement of future phase (vault construction) sequencing and layout
Construction and Design		Waste type, waste form, waste container, infill, wall/base material, cap type	Waste container (Demolition LLW)	Design review taking account of site selection review and site investigation results	Vault walls and base materials	Design review, vault loading strategy, vault aspect ratios	Vault roofs, BPM to repair cracks in Demolition LLW vault walls		Incorporation of overhead crane in future vault phases

Design Area	BPEO 2004 [7; 143]	BPM 2006 [144]	BPM 2007 [145]	BPM 2008 [146]	Optimisation 2010 [147]	Optimisation 2011 [148]	Optimisation 2014 [149]	Optimisation 2020 [51]	Planned Studies
Operational Approach		Temporary roof cover, waste package grouting system, Demolition LLW emplacement, drainage	Vault ventilation, Demolition LLW emplacement, drainage, grouting sequence, backfilling requirements	Drainage and flood management, waste emplacement	Waste classification, backfilling between vault walls and rock	Waste Acceptance Criteria, waste conditioning grout, drainage, flood management, ventilation	Concrete HHISO container, lower drainage system, vault flood management, ventilation, load management in the LLW vault	Change of HHISO, ullage filling, container restacking, demolition LLW waste emplacement, interstitial grouting and vault backfilling	Demolition LLW emplacement
Closure approach			Vault lid, roof removal, final cap, drainage closure, reinstatement			Capping system, enhanced geosphere, drainage closure, institutional control	Capping system		Institutional control

6 SITE CHARACTERISATION

206 This section addresses the detailed requirements in the GRA [19] related to the characterisation of the area or site where D3100 is located. The site characteristics are described, followed by consideration of the potential for future disruption of the site by natural processes and an outline of the programme for further site characterisation.

GRA 6.4.6	**Requirement R11: Site investigation.** The developer/operator of a disposal facility for solid radioactive waste should carry out a programme of site investigation and site characterisation to provide information for the environmental safety case and to support facility design and construction.
GRA 6.4.8(a)	Show that the geological environment is characterised, understood and can be analysed to the extent necessary to support the environmental safety case. This will involve considering, for example, the lithology, the stratigraphy, the geochemistry, the local and regional hydrogeology, and the resource potential of the area.
GRA 6.4.9(a)	The biosphere is characterised, understood and capable of analysis to the extent necessary to support the environmental safety case. This may involve consideration of, for example, topography, soils, surface water systems, flora and fauna distributions and human settlement patterns and activities.
GRA 6.4.14	Site characterisation should involve investigating specific properties of the site and its surroundings in sufficient detail to support the environmental safety case and may include the following: - Local and regional borehole investigations. - Characterisation of soil layers and quaternary deposits. - Characterisation of surface waters and sediments. - Characterisation of surface and sub-surface flora, fauna and ecosystems. - Development of regional and local geological, geotechnical, hydrogeological and geochemical understanding. - Development of the environmental baseline prior to facility construction - Where relevant, consideration of the need to include a phase of underground investigation within the body of the host rock for the proposed disposal facility.
GRA 7.2.6(a)	The ESC should describe all aspects that may affect environmental safety, including the geology, hydrogeology and surface environment of the site.

6.1 Background to Site Characterisation

207 In general, there are three main reasons for undertaking site characterisation:

- Documentation of the environmental characteristics of the D3100 site before construction starts, so as to support the EIA and provide a baseline for assessing and monitoring the impacts of the facilities during construction and operations, and after closure.
- Characterisation of features that have a bearing on the design and construction of the facilities, such as the location, geometry, and properties

of rock layers, the presence of faults, and the direction and volume of water flow.

- Building an understanding of, and constraining, the features, events, and processes (FEPs) at the site that will affect how the facilities will perform. Site characterisation builds confidence in the models and parameter values used in modelling to represent migration pathways and to assess the performance of the facilities now and in the future.

208 Site characterisation activities have been undertaken across the Dounreay area for many years. Summaries of the characteristics of the area to the east of the licensed site (referred to here as the D3100 study area) were prepared in 2000 [190; 191] and 2003 [192] as part of Stage 1 of the D3100 project. This section largely summarises material presented in Site Characteristics Summary 2020 [50], which details the results of site characterisation activities relevant to the D3100 study area; further detail on specific characterisation activities can also be found in Site Characteristics Summary 2014 [193]. Future site characterisation activity, which will be included as it is completed in updates of the Site Characteristics Summary report, is discussed at the end of this section.

6.1.1 Rounds of characterisation

209 An extensive programme of site investigation has been undertaken to support this ESC, the conceptual models used in the PA and to inform the D3100 design and construction. These activities can broadly be grouped into three rounds of work that are discussed below.

Round 1: District-scale investigations

210 Round 1, conducted prior to 2006, was primarily focused on district-scale investigations (i.e. capturing the general characteristics of the Dounreay area) undertaken to support projects on the Dounreay site, such as the Shaft Hydrogeological Investigation Project. The results and interpretations of the Round 1 site investigations were summarised in Site Characteristics Summary 2007 [194].

211 The key investigations undertaken as part of Round 1 included:

- 2002 - Analysis of geosphere sorption: an analysis of sorption of key radionuclides onto the bedrock found at Dounreay was undertaken to inform future performance assessments.
- 2003 to 2006 - Site characterisation work for the Dounreay Shaft Project: work was undertaken to support the development of a preliminary post-closure safety and environmental case for the Dounreay Shaft Project.
- 2005 to 2006 - Dounreay licensed site studies: information on the environment of the Dounreay licensed site and its environs was assembled into a series of site-wide reports. These included a site conceptual hydrogeological model, site water balance, site lithostratigraphy and a summary of hydrochemistry data. These studies were undertaken mostly through consolidating historical data rather than collecting new data.

Round 2: Site-scale studies prior to the start of design and build

212 Round 2, conducted from 2006 to 2011, consisted of site-scale studies focused on both the development of a site conceptual model for the D3100 study area and collection of geotechnical data to inform site selection and concept/scheme design.

213 In 2006, the first issue of the D3100 ESC was accompanied by the first issue of a Site Characterisation Plan (SCP) for D3100 [195]. This covered two "phases" of site characterisation activities[22] up to the start of construction, with activities under Phase 1 for 2006-07 specified in detail and activities under Phase 2 suggested in outline only; herein, both phases are considered as part of Round 2. The SCP was reviewed periodically in light of ongoing work and stakeholder comments, and the Phase 2 characterisation activities were refined accordingly. The results and interpretation of the Phase 1 characterisation were summarised in 2007 in the Site Characteristics Summary and Site Characterisation Plan 2007 [194], which also presented a review of the SCP for ongoing site characterisation work. Several short-term studies were identified to resolve uncertainties and issues that had arisen during implementation and interpretation of the Phase 1 characterisation results, and these studies were undertaken in 2007-08, marking the start of Phase 2 characterisation. During dialogue with SEPA in 2008, it became apparent that the arrangement of boreholes drilled during Phase 1 characterisation would be insufficient to provide a groundwater monitoring network for the D3100 site, partly as a result of altering the design and proposed layout of the facilities in 2007-08. A new suite of boreholes was drilled at the beginning of 2009 (the BM-series). Phase 2 characterisation ended in 2011.

214 To support the 2010 iteration of the ESC (Issue 1 of ESC 2010), Site Characteristics Summary 2010 was prepared [196] based on the results of Phase 1 and Phase 2 characterisation activities undertaken by 2010. An update to the SCP detailing the remaining Phase 2 characterisation activities and subsequent further characterisation was also developed at this time (SCP 2010 [197]). This was updated to SCP 2011 [198] on completion of Phase 2 characterisation. The site characterisation activities up to the start of design and build were used to support *inter alia* the development of geological [199] and local-scale hydrogeological [200] models of the D3100 area.

215 The key investigations undertaken as part of Round 2 included:

- 2006 - Site characterisation activities: borehole drilling and trenching was conducted across the D3100 study area to identify key characteristics of the geology and hydrogeology. This included:
  - Trenching through the Quaternary cover: four 2-m wide trenches were excavated to rockhead across the proposed footprint of the vaults and along the runway.
  - Drilling of LLW-series boreholes: eight deep boreholes, three to 100 m and five to 50 m, were drilled and hydraulically tested to measure groundwater head and hydraulic conductivity. The three deeper boreholes had multi-

[22] The SCP characterisation phases are unrelated to the D3100 construction phases.

level sampling completions installed at 10 m, 20 m and 50 m depths in order to monitor water quality; these have now been replaced in the monitoring network by the BM-series boreholes (see below).

- Drilling of GW1 to GW28 [integer] boreholes: twenty-eight borehole clusters were drilled to a nominal depth of 5 m below ground level and completed by installing slotted pipe in order to monitor water levels and allow sampling.
- Drilling of GW [decimal] boreholes (e.g. designations such as GW5.1): where thicknesses of superficial or weathered material greater than 1 m were identified in the primary GW boreholes, secondary or decimal GW boreholes targeted at the superficial deposits were drilled. Permeability testing of 31 of the GW-series boreholes was undertaken in 2006. Repeat tests of a selection of boreholes were undertaken in 2007. Some of these boreholes are still in use (Figure 6.1).
- Drilling of GT1 and GT2 boreholes: geotechnical study boreholes were drilled to 15 m depth in the proposed vaults area to allow for mechanical testing of recovered rock core and to investigate the geological structure.

- 2006 - Water balance: scoping work was undertaken on the water balance for the D3100 surface water catchment mapping drainage, discharge points and the catchment boundary.
- 2007 - Geophysical survey: shallow investigation methods were selected to provide comprehensive coverage of the near-surface structure of the study area through a series of transect lines 100-200 m apart.
- 2007 - Coastal logging: lithostratigraphic logging of a 1,650-m long coastal section of cliffs adjacent to the study area was correlated with the lithostratigraphy from the deep LLW-series boreholes.
- 2009 - Ground investigation works: ground investigations were undertaken to develop an understanding of the ground conditions within the D3100 study area. These included:
  - Drilling of BM-series boreholes: thirty-nine Baseline Monitoring (BM) boreholes were drilled to establish a groundwater monitoring network around the proposed vault locations. The boreholes are arranged in clusters of three at thirteen locations. Each location comprises a shallow borehole (BM#.3 – few metres into weathered bedrock), an intermediate borehole (BM#.2 – around 10 m), and a deep borehole (BM#.1 – around 20 m) corresponding to the anticipated depth of the excavations for the vaults. Rising and falling head permeability tests were undertaken, together with coring and geophysical logging. These boreholes, together with a selection of the GW boreholes, were completed for groundwater level monitoring and groundwater quality sampling, which commenced in March 2009 (Figure 6.1).
  - Drilling of inclined boreholes: four inclined boreholes (GT3, GT4, GT5 and GT6) were drilled within two areas of the D3100 footprint at an angle of 45 degrees from the vertical and in orthogonal directions selected to

intersect dominant joint sets. The boreholes were 28 m long, were cored and logged, and provided samples for geotechnical testing.

- 2009 - Discontinuity mapping: discontinuities in the rocks exposed in the cliffs and foreshore on a section of the coast north of the planned site were mapped to characterise the dominant discontinuities in the rock mass.
- 2009 - Baseline radiological survey: a radiological survey of the ground surface across the study area was carried out using the Groundhog system. DSRL then conducted an investigation into the contamination finds.
- 2006 to 2011 - Pre-construction groundwater and surface water monitoring: groundwater levels and surface water and groundwater quality were monitored in order to define the baseline conditions prior to Phase 1 construction.
- 2010 to 2011 - Non-radiological land contamination investigation: an assessment was undertaken to identify pollutant linkages associated with potential sources of non-radiological soil contamination in the D3100 study area.
- 2006 to Present - Characterisation database development/maintenance: the IMAGES (Information Management and Geographical Evaluation System) database maintained by DSRL contains the radiological information for soil and rock samples from the study area (e.g. collected from the 2006 and BM-series boreholes) along with more general invasive survey (e.g. borehole logging) and ground water monitoring data. The database is still actively maintained and has been updated with recent (Round 3 – see below) characterisation data.

Round 3: Site characterisation activities since the start of design and build

216 Round 3, conducted post-2011, has generally consisted of excavation-scale investigations focusing on detailed geotechnical design and has run in parallel with the detailed design and construction of the facilities. Detail on Round 3 activities (along with Rounds 1 and 2) can be found in the 2014 and 2020 Site Characteristics Summary reports [50; 193].

217 The key investigations undertaken as part of Round 3 so far include:

- 2011 to 2012 - Further geological mapping: investigation of cores from geotechnical boreholes in the footprint of the vaults and from the Landfill 42 area, mapping of exposed bedrock surfaces of the planned Phase 1 vaults and part of the area of the enhanced geosphere layer following stripping of the overburden, and mapping undertaken in the excavations of the first two vaults, including mapping of the floor slabs. The resultant summary report updates and refines the site geology, and confirms the validity of the geological model [201].
- 2012 - Further local-scale hydrogeological modelling: the 2010 Base Case for the local-scale hydrogeological model [200] was updated and refined as the 2012 Base Case [202]. The 2012 Base Case was developed further to implement the enhanced geosphere in order to simulate the hydraulic regime

following closure of D3100 and provide input data for the Run 4 and 5 PA models.

- 2011 to 2014 - Ground investigation (GI) for construction: the Design-and-Build Contractor's Site Characterisation Plan is included in SCP 2011 [198]. The Ground Investigation Report (GIR) [203] contains information from twenty-four trial pits, twenty-one trial trenches, eighteen geotechnical boreholes (the BC Series), two trial interceptor drains (deep and shallow), and *in situ* geotechnical testing. In addition, detailed fracture logging, laboratory testing for rock mass properties, and rock slope stability assessments were performed as part of the GI works. Two new boreholes (BC16 and BC17) for PPC monitoring and five trial pits (TP20 to TP24) for GI were also developed for the temporary stockpile for soil and rock excavated from the Phase 1 vaults (see to right of vaults on Figure 5.5).

- 2011 to Present - Groundwater and surface water monitoring: quarterly groundwater and surface water monitoring has been undertaken and reported (e.g. [204]). This monitoring has recorded changes in groundwater and surface water associated with groundwater pumping since Phase 1 construction. The borehole series BM9.#, BM10.# and BM11.# were decommissioned in December 2011 as they lay within the footprint of the planned excavations, but they were replaced and monitoring was continued in the replacement borehole pairs BC09 & BC09.1, BC10 & BC10.1 and BC11 & BC11.1.

- 2019 - Drilling of replacement boreholes: two further clusters of new BC-series boreholes were drilled (BC-18 and 19; Figure 6.1) to replace boreholes expected to be lost at the start of Phase 2 construction.

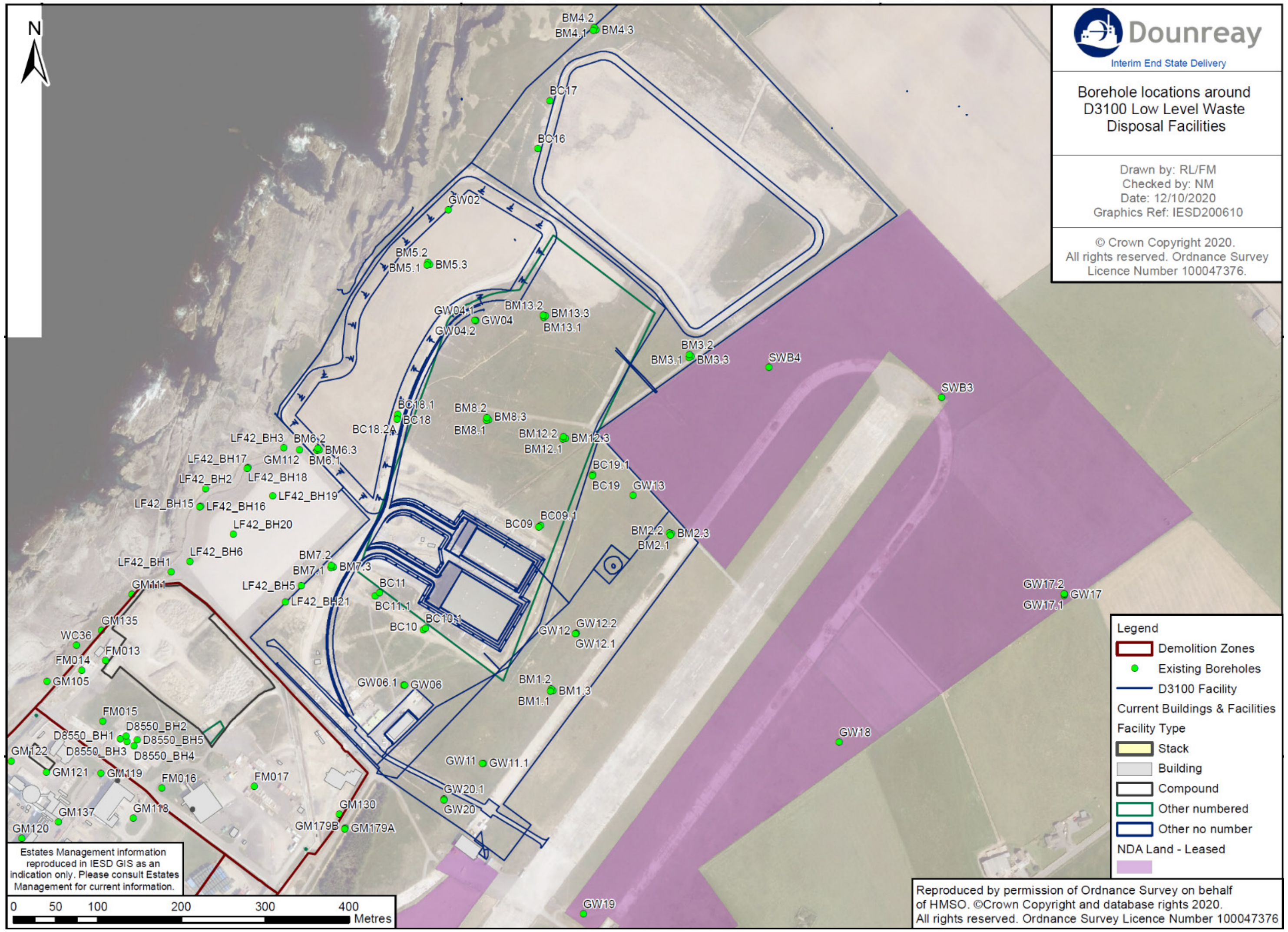

Figure 6.1: Current maintained borehole network in and around the D3100 site as of October 2020.

6.2 Site Characterisation Topics

218 For the purposes of summarising information on the site characteristics in this section, six key site characterisation topics are described in relation to the GRA requirements set out in [19, ¶6.4.8 and 6.4.9]:

- physiography and land use;
- geology, including stratigraphy, lithology and structure;
- climate;
- hydrogeology, including surface water balance and local and regional groundwater flow;
- geochemistry, including groundwater geochemistry and the retardation properties of the geosphere; and
- resource potential.

6.2.1 Physiography and land use

219 The Dounreay nuclear licensed site (National Grid Reference: E299554 N967976) is located on the north coast of Scotland in the county of Caithness, approximately 13 km west of Thurso (Figure 1.1). The D3100 site is adjacent to the north-eastern boundary of the Dounreay nuclear licensed site. A redundant airfield runway runs parallel to the D3100 site to the south (Figure 6.2).

220 The D3100 site lies on a gently sloping (approximately 2º) coastal plain about a kilometre in width (Figure 6.3), terminating in sea cliffs ca. 10 to 15 m high. The slope rises gradually to about 50 m Above Ordnance Datum (AOD) elevation close to the main road, the A836, which runs parallel to the coast ca. 1 km inland. South of the road, low hills rise to ca. 130 m AOD elevation (e.g. the Hill of Shebster is 132 m high), while hills directly SE of D3100 rise to 90 m. “Geos”, or narrow inlets, intermittently dissect the cliff line, following faults that are more readily eroded.

221 Offshore, the sea bed slopes fairly steeply from depths of -20 m to -40 m AOD and, thereafter, more gently to maximum depths of around -100 m AOD in a northerly direction [190, ¶8]. Depths in the Pentland Firth and to the west of Orkney tend to vary between -50 m and -100 m AOD. In a northwest direction away from the cliff line, the foreshore and seabed are composed of bare rock for up to 400 m offshore, before a sand cover is encountered [190, ¶8].

222 The topography of the D3100 site following closure will be modified by the installation of the enhanced geosphere and the cap, with the land elevated between the vaults and the cliff-line. This is shown in Figure 6.4, with an illustrative cross-section in Figure 5.9.

Figure 6.2: Aerial photograph (taken ca. 2013) of the Dounreay licensed site and the D3100 site looking east. The photograph illustrates the flat coastal plain gently sloping towards the sea, covered generally by grass and rough pasture and terminating against the cliffs and rocky foreshore.

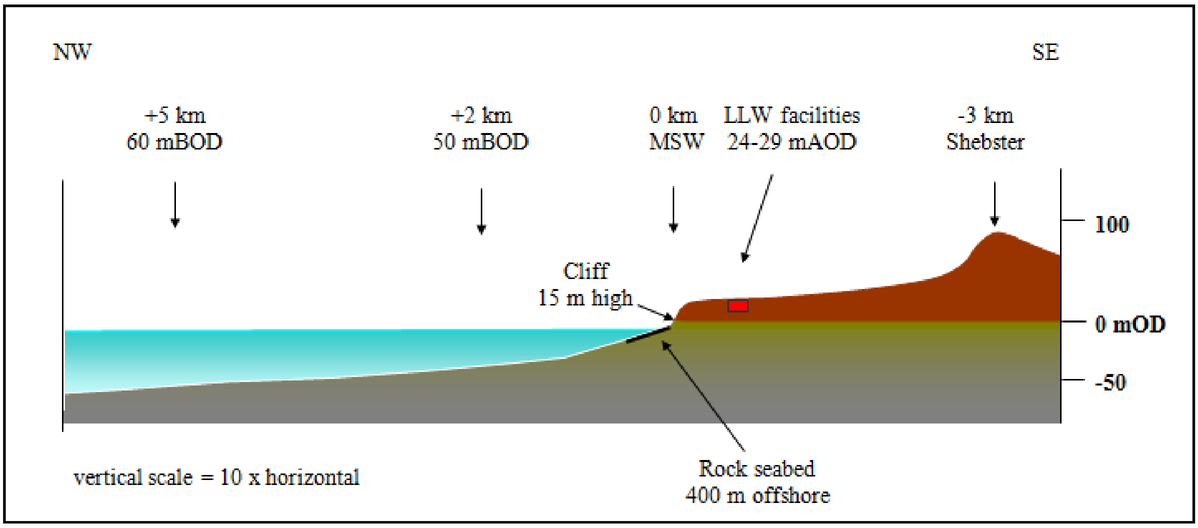

Figure 6.3: Topographic cross-section running NW-SE through the location of D3100 (adapted from [190, Fig.2.2]).

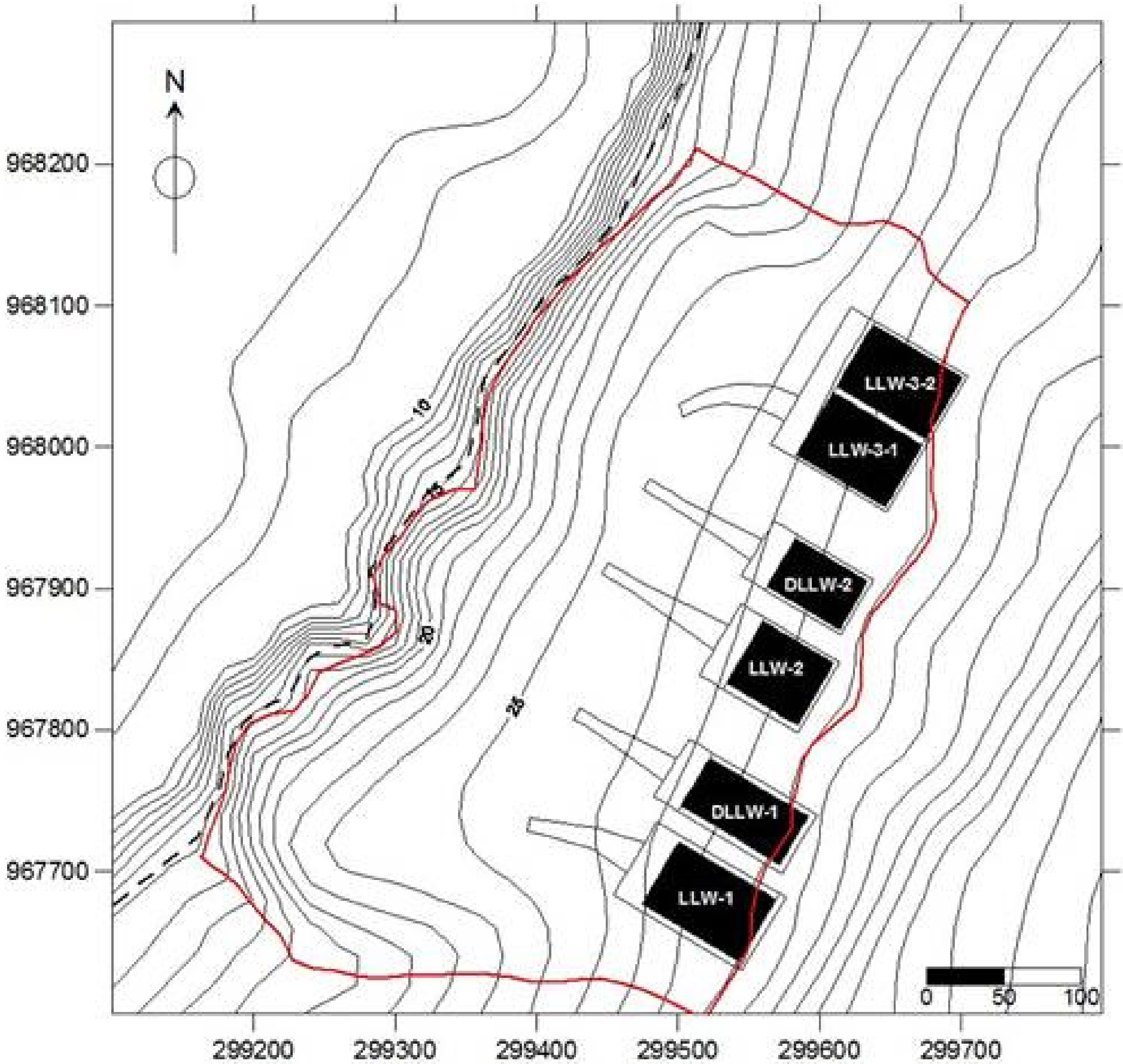

Figure 6.4: Proposed full extent of the enhanced geosphere between D3100 and the coast following closure (red line). The indicative positions of the vaults are shown (shaded boxes; note order may change), along with the inner excavation perimeters and the access roads into the vaults during excavations (black lines). The black dotted line indicates the top of the cliffs (contours in mAOD). Adapted from [202, Fig.3.3(b)].

223 In the coastal region containing the Dounreay and D3100 sites, the local farmland, which consists mostly of pasture, is organised around drain and ditch networks that tend to discharge directly over the cliff tops. The gently sloping land along the coast is generally given over to grazing of cattle and sheep on rough and improved grassland (Figure 6.5). The general thinness of the soil and the strong winds inhibit the growth of trees locally.

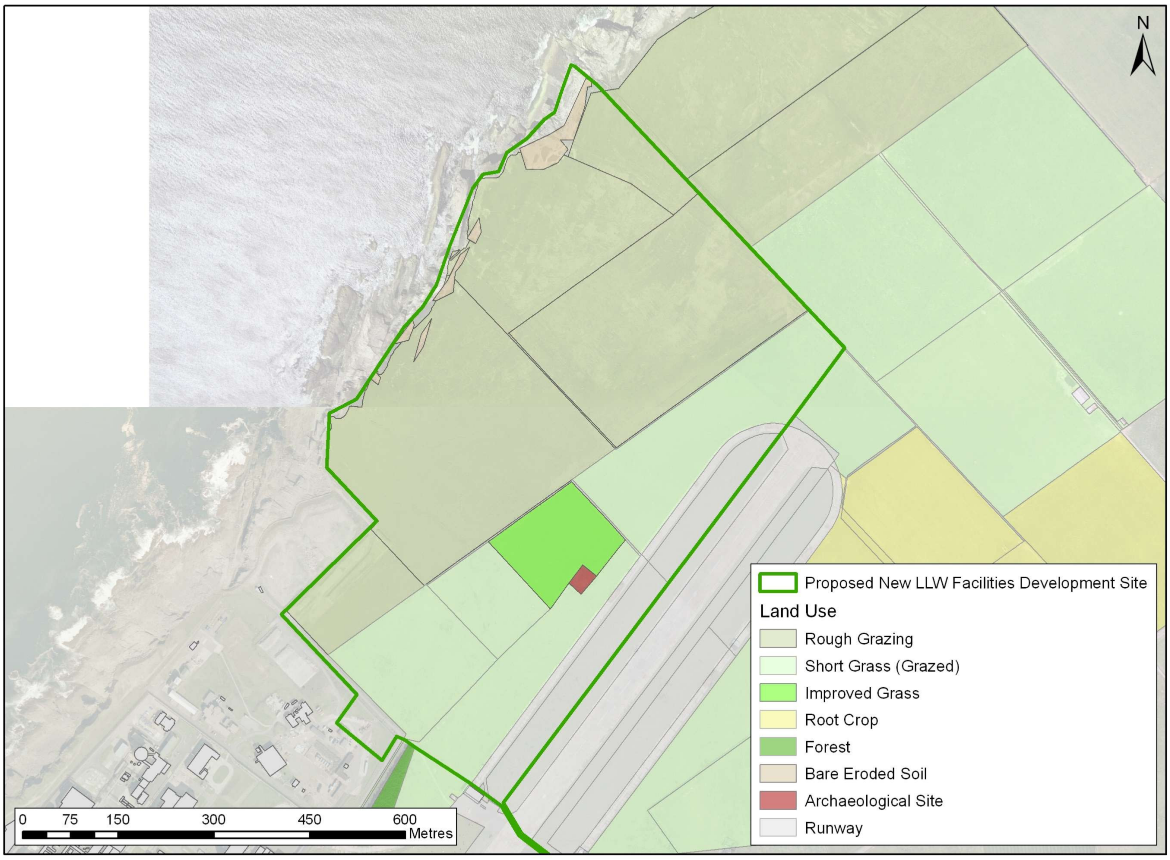

Figure 6.5: Land-use around D3100 before construction (based on [205]).

224 The low quality of the land around D3100 means that land use is limited to grazing. Land use in the wider area around Dounreay is summarised in a series of habits surveys conducted on behalf of SEPA in 1999 [206], 2003 [207], 2008 [208] and 2013 [209]. A more recent habits survey has recently been undertaken, but the results have yet to be published.

225 The coastline close to D3100 is rocky and can be laborious to traverse. An access track has been constructed around the perimeter of the site to allow access to the cliff line. With the exception of walking above the foreshore, no activities were reported close to the Dounreay and D3100 sites on the foreshore or cliff line in the 1999, 2003, 2008 and 2013 surveys [206, p.17; 207, p.20; 208, p.24; 209, p.26]. Local interviewees suggested that Oigin's Geo, located close to the D3100 site boundary, is infrequently visited for fishing (one individual in 2003 [207, p.20]), or walking (one and two individuals in 2008 and 2013, respectively [208, p.24; 209, p.26]). The presence of winkles, a species of small edible marine sea snail, was investigated in 2003, but none were observed [207, p.20].

226 The 2003 and 2008 surveys suggested that less than 20% of the crustaceans, and an even lower percentage of the fish, landed at harbours around Dounreay came from the survey area (20-km radius from the Dounreay marine discharge pipe) [207, p.23; 208, p.27]. Note that there is a 2 km fishing exclusion zone around the Dounreay site pipe outfall imposed by the Food Standards Agency within the survey area.

227 Farming in the Dounreay area is predominantly beef and lamb production. Several farms also keep hens for egg production. No dairy herds were identified in any of the surveys [206, p.32; 207, p.32; 208, p.52; 209, p.41]. A few households or smallholdings consume locally-reared chicken eggs and, less frequently, chicken meat [206, p.32; 207, p.32]. Crops produced on local farms are mainly used for winter feed for the livestock [206, p.32; 207, p.32; 208, p.46; 209, p.41]. Local households grow fruit and vegetables, including potatoes, swede and turnips, soft fruits, beans, onions, salad vegetables, herbs and apples [206, p.32; 207, p.32; 208, p.46; 209, p.41].

6.2.2 Geology

228 The geology of the D3100 study area is relatively simple, consisting of a thin layer of superficial Quaternary deposits overlying Devonian bedrock. The geological succession is summarised in Figure 6.6.

Figure 6.6: Summary of the geological succession in the D3100 study area. The Pleistocene ran from approximately 2.5 M years to 11,700 years before present, while the Middle Devonian ran from approximately 393 M years to 383 M years before present.

Quaternary cover

229 In 2006, trenching to rockhead was undertaken by the D3100 project across the study area to provide information on the thickness and composition of Quaternary deposits, and to facilitate identification of the surface traces of significant faults. Four trenches were excavated [210]. Where easily excavated weathered rock was encountered, the excavation was progressed until competent rock was encountered. The strata encountered in the trenches were generally classified into four broad categories: top soil, diamicton (hereafter referred to as till), weathered rock, and rockhead or unweathered bedrock. These categories are described in the following paragraphs. In addition, sequences of Made Ground associated with the runway were also identified.

230 The soil encountered in the trenches was generally a yellowish-brown or grey-brown silty top soil [210, p.33]. It was generally fairly thin, the base varying from 0.1 m to 0.4 m in depth. Thicker soils tended to be found to the east, where they tended to be more organic rich and almost peaty in nature.

231 Till was found overlying bedrock throughout the areas to the northwest of the runway. The till encountered varied in thickness from 0.1 m to a maximum of 1.25 m, with an average of about 0.5 m. The occurrence of the till is consistent with British Geological Survey (BGS) characterisation of Quaternary cover in the Dounreay area [211]. The D3100 site lies in the Till Domain on the BGS map of Quaternary cover, with the till being identified as the Forse Till, a member of the Banffshire Coast and Caithness Glacigenic sub-group containing material derived from the Moray Firth [211]. Within the D3100 area, the Broubster Till, which is found to the west, has not been recognised as a separate unit.

232 Throughout the study area, the till appears to be broadly similar, consisting of a mottled grey-brown to yellow-brown, firm to stiff clay with varying quantities of clasts [210, p.33]. Occasionally, clasts of granite, metamorphic rock and red sandstone occur. The relative quantities of clasts within the till are variable. Particle size distribution analysis highlights that the till varies from being matrix dominated (70% - 80% clay/silt) to being reasonably undifferentiated, with the clay/silt, sand and gravel fractions all constituting approximately 30% each [212]. X-ray diffraction analysis identifies that the till samples are all composed of broadly the same mineral assemblage - quartz (43%), feldspar (albite 24%, potassium feldspar 14%), undifferentiated mica species (7%), chlorite (11%), and traces of pyrite (1%). The clay fractions are dominated by illite and chlorite.

233 The till appears to be relatively continuous across the D3100 site, except in the area between the main runway and the south-eastern taxiway. Anecdotal evidence suggests that during the construction of the runway the area to the southeast was scraped down, with material deposited to the northwest, in order to level the ground. This is supported by the identification of Made Ground northwest of the runway. Made Ground has been identified in layers up to 2.6 m thick [210, p.33; 213, Tab.3], although an interpretation of geophysical data suggests that the sequence could be thicker in places.

Bedrock geology

234 The Middle Devonian bedrock in the region around D3100 is composed of sedimentary Caithness Flagstones of the Crosskirk Bay and Dounreay Shore formations (Figure 6.7). They are lacustrine deposits in a geological structure known as the Orcadian Basin, which was formed by extension and gravitational collapse during the Devonian geological period. The Devonian rocks lie unconformably on top of older metamorphic Precambrian basement intruded by younger Caledonian igneous rocks (e.g. the Reay Diorite to the southwest of Dounreay). The unconformity between the Devonian rocks and underlying basement crops out around 2 km to the south of the Dounreay licensed site. Owing to the regional dip of the strata, at around 10° to the northwest, the Devonian sediments are some 300 m to 500 m thick beneath Dounreay (Figure 6.7).

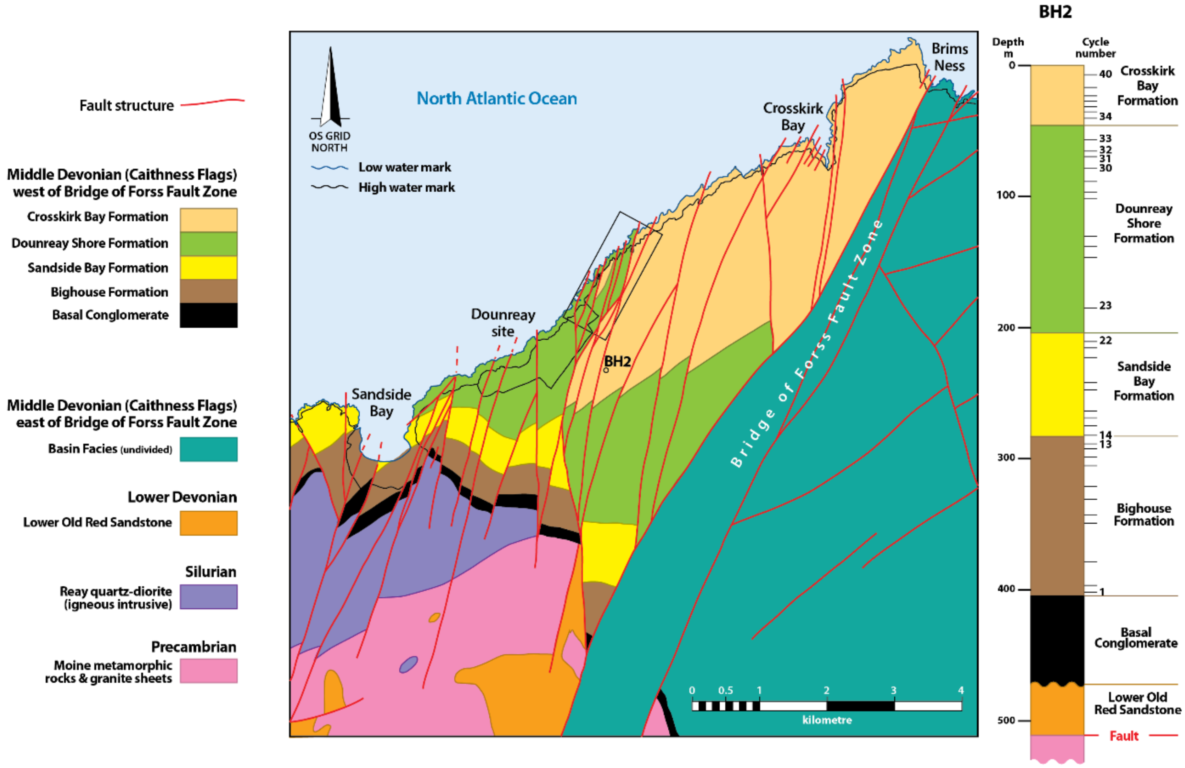

Figure 6.7: The geological structure of the bedrock of Dounreay [201, Fig.2.1]. The rectangle roughly in the centre of the map denotes the location of the D3100 site.

235 The Crosskirk Bay and Dounreay Shore formations are characterised by cyclic sedimentary sequences or cyclothems 5 m to 10 m thick. The cyclothems can be categorised in terms of lithofacies that reflect different depositional lacustrine environments changing from fine muddy sediments to coarse sandy sediments and back again [201; 214]:

- A - Finely laminated layers of calcium carbonate, dark bituminous mudstone and siltstone, often with fossil fish remains.
- B - Finely laminated layers of dark bituminous mudstone and siltstone.
- C - Alternating grey to green mudstones and siltstones.
- D - Assemblages of fine-grained to medium-grained, pale-grey sandstones in individual layers up to 25 cm thick, with thin muddy siltstone interbeds.
- In addition, some coarser sandstone units more than ca. 1 m thick (sometimes termed Lithofacies E) are present in parts of the sequence. Layers of coarse-grained conglomerate (containing rounded pebbles and boulders) and sedimentary breccia (containing angular pebbles and boulders) are also sometimes present near the base of the sequence.

236 A fully-developed cyclothem has an upward sequence of ABCDCB and is succeeded by the next cyclothem. The A units are considered to be approximate time planes defining the maximum extent of the lake in the Orcadian Basin during each cycle, and were numbered upward in the deep boreholes drilled as part of the Nirex

investigations in the 1990s [215]. Later boreholes and foreshore mapping showed that additional A horizons could be developed within the B units, and that some cycles did not have A units. The revised stratigraphy developed for the D3100 project in [214] therefore uses B units to define the cycles (Figure 6.8), but the original numbering scheme developed in earlier studies has been retained for continuity.

237 Mineralogical analysis of the Devonian bedrock in the D3100 study area has been undertaken on samples covering lithofacies A to D [216]. All four lithofacies contain major detrital quartz, albitic plagioclase, K-feldspar with subordinate to minor detrital muscovite, biotite and chloritised biotite. Apatite, monazite, zircon, ilmenite, magnetite and rutile are present as trace detrital minerals. This is in agreement with mineralogical analysis undertaken on more recent fractured cores from the D3100 study area which contained very similar compositions [217, §5.1]. The bedrock at the site can also contain high proportions of clay, present either as discrete clay laminae or as matrix clays, composed largely of illite, chlorite and corrensite [217, §5.1]. Fractures within the bedrock, where infilled, contained calcite-pyrite mineralisation [216, ¶50; 217, §5.1].

238 The Devonian bedrock exhibits significant diagenetic alteration with the development of major authigenic quartz, albite and potassium feldspar overgrowth cements. Weakly ferromanganoan calcite, ferroan dolomite and ankerite are also present as major intergranular pore-filling cements [216, ¶133; 217, §5.1]. Pyrite is present as a minor to trace mineral, occurring in a variety of forms: disseminated fine crystals in the matrix; replacing detrital micas; as pseudomorphs after early diagenetic evaporite minerals; and as coarser discontinuous and irregular lenses or patches replacing the matrix [216, ¶62; 217, §5.1]. Trace amounts of uraniferous hydrocarbon (bitumen) have been identified in two analysed samples [216, ¶62].

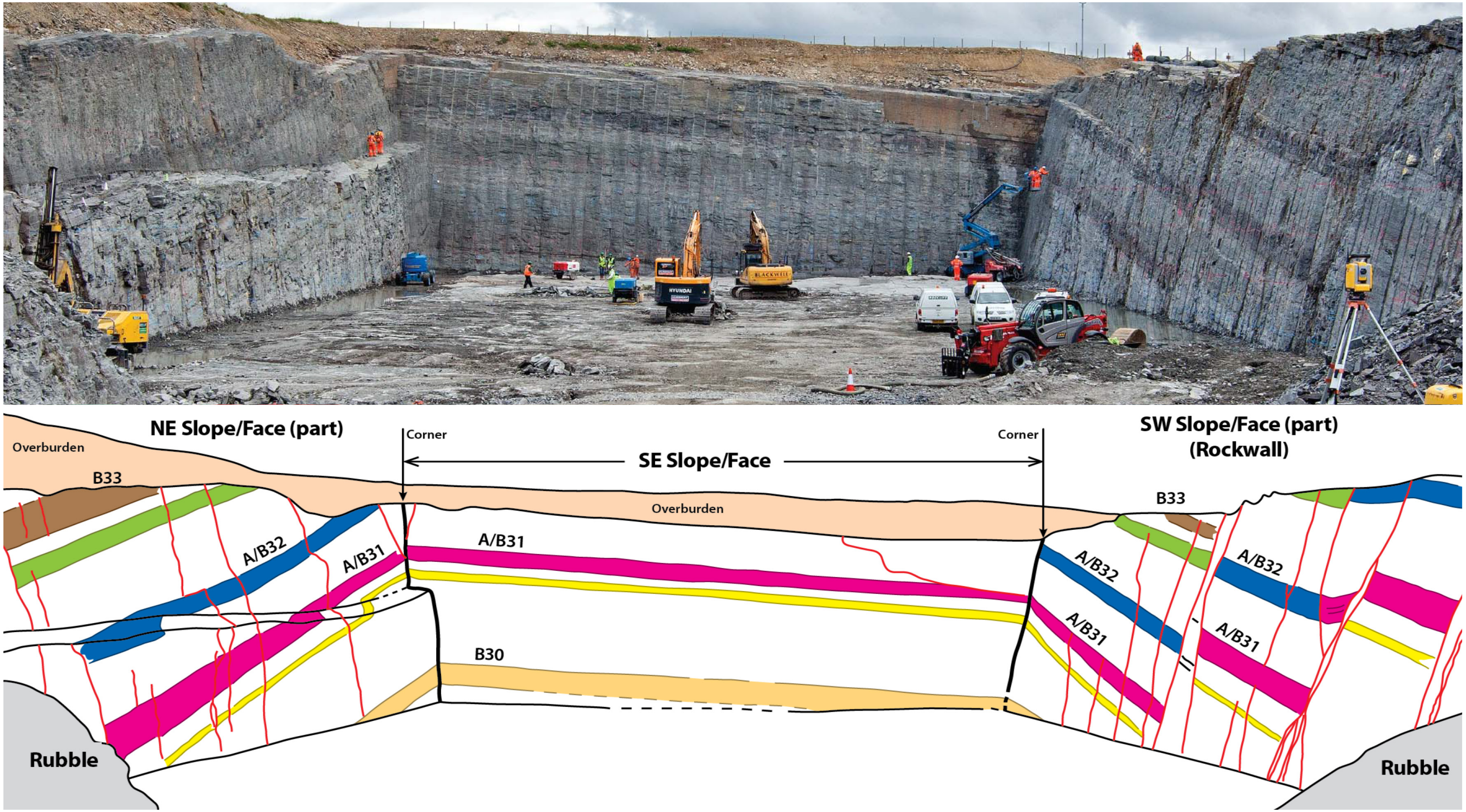

Figure 6.8: Photograph and geological interpretation of D3130 slope excavations in the Dounreay Shore Formation [201, Fig.4.7].

Quaternary structure

239 There is no evidence for structural disturbance of the Quaternary cover. The BGS study of Quaternary deposits [211] identifies a deformation till, but the deformation is related to glacial shearing rather than structural disturbance (i.e. no faulting, or compressional/extensional stress). The BGS study [211] also notes that only weathered tills are fractured and oxidised; otherwise, in the unweathered tills, fracturing is minimal or absent.

Bedrock structure

240 Interpretation of the structure of faulting of the Middle Devonian rocks prior to 2003 was based primarily on mapping of exposures along the foreshore, where exposure of faults is good, and interpretation of the seismic survey of the Dounreay area by Nirex [218]. However, the seismic survey was a low-energy seismic reflection study utilising reflection of seismic waves from a sandstone unit at several hundred metres depth below the Dounreay site. This depth of reflection meant that the recognition of the position of fault displacements at depth had a high uncertainty in projection of the position of the fault displacements at the surface.

241 More detailed studies of faulting, including a localised seismic survey, were conducted as part of the investigations of the geological structure around the Dounreay Shaft [219]. However, the studies did not extend to the D3100 study area. Site characterisation studies undertaken by the D3100 project since 2006 have supported further revision of the structural interpretation. Figure 6.9 shows the structural interpretation for the D3100 study area and Figure 6.10 shows the fault structures in the vicinity of the Phase 1 vaults. These figures, from the most recent structural interpretation [201], have been built upon earlier interpretations (e.g. [220]) and from recent geological mapping of bedrock exposed in geotechnical boreholes, on scraped rock surfaces, and in the Phase 1 excavations.

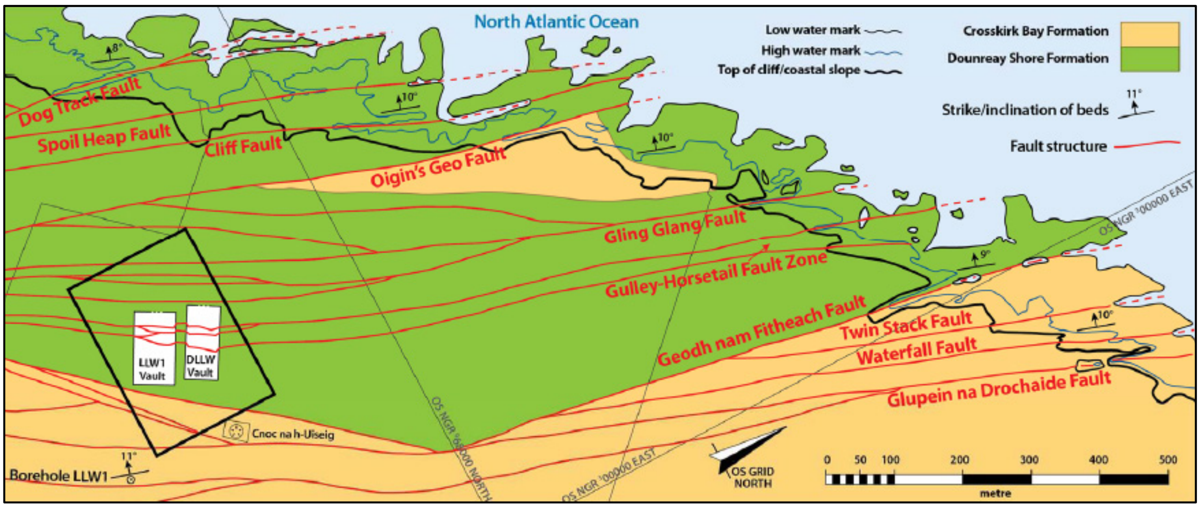

Figure 6.9: Interpretation of the geological structure of the D3100 study area [201]. The rectangular area of the vaults in the box is shown in detail in Figure 6.10.

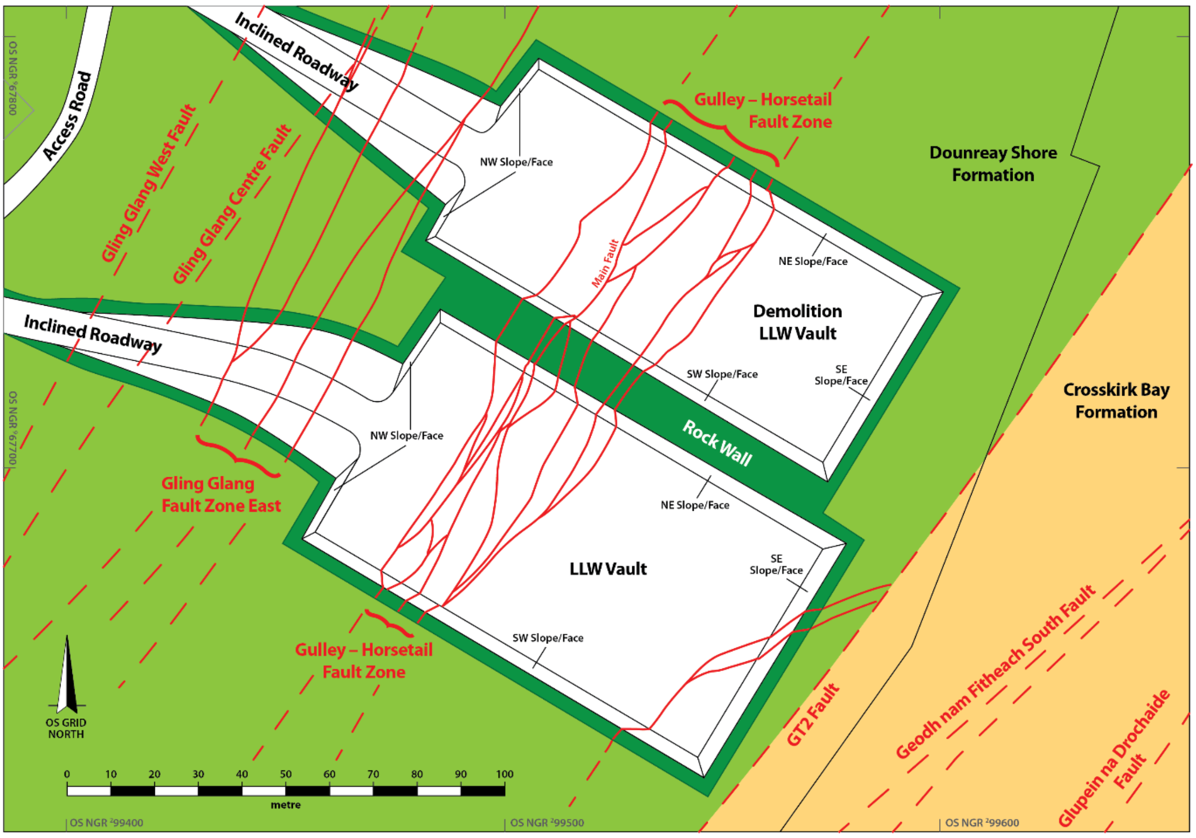

Figure 6.10: Interpretation of the geological structure of the Phase 1 vaults area [201].

242 Outcrops of the Middle Devonian rocks in the foreshore at Dounreay show that the sequence is off set repeatedly by a series of north-northeast south-southwest faults. The structural setting of the D3100 site is defined by the north-south trending Dog Track Fault to the west and the Geodh nam Fitheach and Glupein na Drochaide Faults to the east. Within the D3100 study area, the displacement associated with the Dog Track Fault is transferred to the Geodh nam Fitheach Fault Zone (Figure 6.9).

243 The rock exposures in the two vault excavations have revealed details of the internal structure of the main fault that crosses the vault locations, the Gulley – Horsetail Fault Zone (e.g. Figure 6.8). Multiple phases of development of this fault zone have produced a series of fault segments that are linked laterally (and probably at depth). Examination of the fault structures has identified the time sequence and nature of the displacements, and also the series of mineral infillings [201]. Geological mapping of the excavations for the Phase 1 vaults has shown agreement with the geology and geological structure interpreted from surface-based investigations.

244 A 3D visualisation of the geological structure of the study area was developed in EarthVision in 2003 [221]. The stratigraphical mapping results and geological structures for the D3100 study area have been incorporated by DSRL into its VULCAN modelling system. The VULCAN model allows 3D visualisation of the geological structure of the site study area at the lithofacies scale (m). The model was peer reviewed and found to be fit for purpose [222]. The model comprises interpretative elements; surfaces representing faults, stratigraphic units and surface

fault traces, and also supports investigation data from pre-existing and new boreholes, and surface outcrop geological logging.

Jointing and bedding

245 The mean orientations of the major discontinuities derived from stereographic projection analysis of data from the trial trenches and the 2011 ground investigation boreholes (BC-series) are as follows (dip/dip direction in degrees, plus spacing and aperture widths) [203]:

- Bedding: 08°/280°. Spacing ranged from 200 mm to <20 mm (thinly bedded to thinly laminated). Apertures varied between 0.1 mm and 10 mm, depending on the degree of weathering.
- Joint Set A: 83°/126°. Majority close to medium spaced (60 mm to 200 mm). Majority of apertures in range of 0.25 mm to 20 mm (partly open to open), with occasional wide open joints with apertures up to 100 mm (where weathered).
- Joint Set B: 86°/049°. Medium to widely spaced (200 mm to 2 m). Apertures in range from <0.1 mm to tens of centimetres, with majority ranging 2.5 mm to 20 mm (partly open to open) and 0.1 mm to 0.25 mm (tight). As with Joint Set A, there were occasional wide open joints with apertures up to 100 mm (where weathered).
- Joint Set D: 88°/159°. Majority close to medium spaced (60 mm to 200 mm). Most apertures ranged 0.25 mm to 20 mm (partly open to open).

246 Joint Set C identified in the foreshore discontinuity mapping study [223] was not apparent from this analysis.

247 Joint spacings tend to increase with depth. The infill material of the discontinuities was most commonly secondary calcite, especially below about 5 m depth away from the effect of near-surface weathering [203]. Other infill materials include clay, pyrite and bitumen.

Weathering

248 Weathering features have been observed within the superficial deposits in the region surrounding the D3100 site. Within unweathered tills, fracturing is minimal or absent. However, as weathering increases, tills increasingly fracture and oxidise, resulting in increases in hydraulic conductivity values [211, p.39].

249 The degree of weathering across the Devonian bedrock lithofacies varies, with Lithofacies D tending to be more resistant [210, p.15; 224, §2.3.1]. Results of borehole coring, trenching and geophysical surveys suggest that the intensity and depth of weathering and alteration of the bedrock is increased along lines of faulting [210, p.14; 224, §2.3.1]. As a result, the topologies of the inferred weathered bedrock are extremely uneven, consisting of deep, narrow grooves oriented approximately north-northeast by south-southwest (Figure 6.11).

250 On the basis of the geophysical data obtained in 2007 and core observations, Michie and Bond [224] divided the upper bedrock into weathered and altered layers (with

unaltered rock beneath). The characteristics and definitions of the weathered and altered material are summarised in Table 6.1 in terms of geophysical and geotechnical properties. However, note that no correlation has been found between the altered and unaltered layers of bedrock that are differentiated geologically and geophysically and the hydraulic properties or the groundwater flow regimes discussed later in this section.

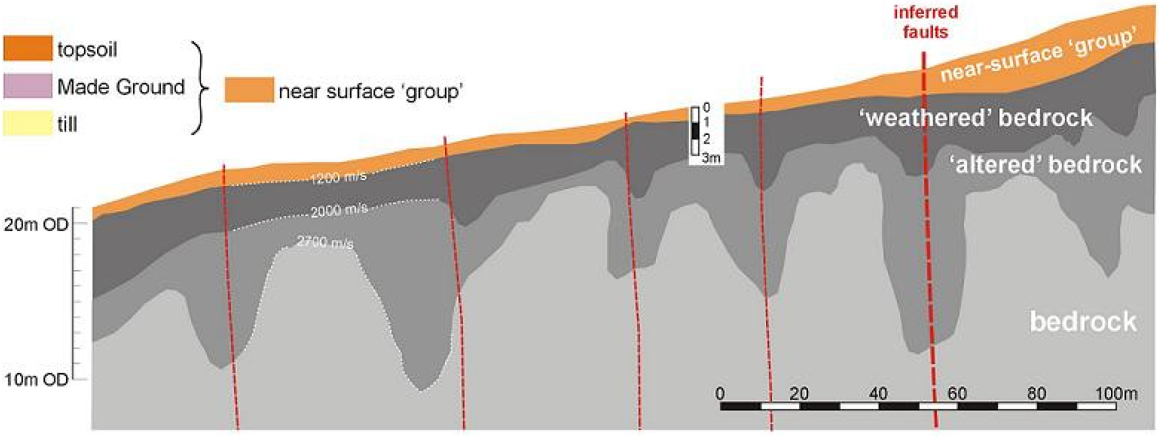

Figure 6.11: Schematic section showing increased depth of weathering interpreted along lines of faulting [224].

Table 6.1: Devonian bedrock alteration characteristics [224].

	Qualitative Description	Quantitative Description	Average Depth	Max Depth
Weathered Bedrock	Pervasive, surface-related weathering and disaggregation. Obvious signs of oxidation.	RQD * < 30% FI ** > 15 Seismic velocity: 1200 m s^{-1} to 2000 m s^{-1}	4.10 m	6.5 m
Altered Bedrock	Evidence of surface-related weathering and evidence of structural disturbance or chemical changes due to faulting.	RQD < 75% FI > 5 Seismic velocity: 2000 m s^{-1} to 2700 m s^{-1}	11.7 m	21.5 m

* Rock Quality Designation. ** Fracture Index = number of natural core fractures per metre.

251 Within the bedrock, the most abundant weathering process is pyrite oxidation, with concomitant growth of iron oxyhydroxides such as goethite [225]. This process produces the brown staining observed adjacent to water-bearing fractures, commonly seen in the upper tens of metres of the bedrock at Dounreay. However, evidence of such weathering was not seen below a few metres depth in the D3100 study area boreholes (e.g. [224, App.C]). Mineralogical evidence of dissolution of feldspar adjacent to fractures containing groundwater has also been reported [225].

252 Many of the fractures and fracture surfaces show clear evidence of water-rock interaction, with oxidation of pyrite (and probably also marcasite). The alteration may penetrate up to 15 mm from the fracture surface. However, the degree of alteration decreases with depth, and appears to be limited mainly to fractures above about 10 m depth [217, §5.1]. Pyrite oxidation is closely associated with significant enhancement

of the porosity in the narrow zones of altered wallrock. The enhanced porosity results largely from the dissolution of calcite and dolomite/ankerite cements and increases the potential for rock matrix diffusion processes [217, §5.1]. In addition, it exposes clay minerals such as corrensite and illite to groundwater interaction, which may be significant with regard to cation exchange and sorption of radionuclides [217, §5.1]. The precipitation of fine-grained iron and manganese oxides on pore walls also significantly enhances the potential of pore surfaces in the altered wallrock to sorb radionuclides from diffusing porewaters [217, §5.1]. Barite also seems to be a late-stage precipitate associated with the recent groundwater system.

6.2.3 Climate

253 A description of the biosphere in the area of interest for D3100, including a general description of current temperate climate conditions, was compiled for the Run 1 PA [191]. A more detailed description of the climate conditions affecting surface hydrology is provided in [226] and [227]. A more recent climate analysis presented in [50] is summarised below.

254 The UK Government, via the Met Office and Defra, produces climate projections in order to understand and assess plausible future climate changes. As part of the UKCP09 data set (downloaded from the Met Office website[23] in [50]), past climate variables (e.g. mean daily maximum temperature, mean daily minimum temperature, precipitation) are available for the UK at a 5 × 5 km resolution. Table 6.2 presents average monthly and annual weather patterns at the D3100 site over longer (ca. 100 years) and shorter (ca. 10 years) terms. Data presented are for the 5 × 5 km square centred on grid reference E297500 N967500 (ca. 1 km west of the site).

255 Average temperatures at the site are lowest in January and February and highest in July and August (Table 6.2). Recent temperatures at the site have been ca. 0.5°C warmer than the long-term average. Long-term rainfall averages suggest April, May and June tend to be relatively dry, with rainfall higher during the rest of the year (Table 6.2). Potential evaporation data are available during the last couple of decades for Wick airport and for a few years at Kirkwall. Based on data from these sites, the average evaporation value for the D3100 study area for the period 1991 - 2004 is estimated as 501 mm y^{-1}, varying between 452 and 527 mm y^{-1} [227, Tab.5.13].

256 The region is noted as being windy. Data obtained from the weather station at the former visitor centre show that between 2006 and 2009, the mean monthly wind speeds ranged from 4.1 to 7.3 m s^{-1}. Wind speeds exceed 5.7 m s^{-1} for over 60% of the time. The most frequent wind direction is south-southeast, prevailing for 14% of the time. The high winds in the region could lead to erosion of exposed soils; however, most areas (whether under agricultural production or not) have sufficient vegetation to reduce soil erosion.

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[23] Met Office gridded land surface climate observations - monthly climate variables at 5 km resolution (UKCP09) https://catalogue.ceda.ac.uk/uuid/94f757d9b28846b5ac810a277a916fa7

Table 6.2: UKCP09 climate data for E297500 N967500, adapted from Met Office data in [50, Tab.2.1]. Long-term averages are taken from 1910–2016, except for average wind speed, which is taken from 1969–2014. Recent averages are taken over the period 2006–2016, except for average wind speed, which is taken from 2006–2014. Long-term and recent temperature values are derived based on monthly mean values of daily maximum and minimum air temperature.

Month	Long-term ave. max. temp. (°C)	Recent ave. max. temp. (°C)	Long-term ave. min. temp. (°C)	Recent ave. min. temp. (°C)	Long-term rainfall (mm)	Recent rainfall (mm)	Long-term ave. wind speed (m s^{-1})	Recent ave. wind speed (m s^{-1})
Jan	6.7	7.3	1.2	1.8	95.6	112.9	6.5	6.4
Feb	7.0	7.9	1.2	1.8	65.2	69.1	6.3	6.2
Mar	8.4	9.1	2.1	2.7	62.4	62.9	6.3	6.3
Apr	10.1	11.2	3.5	4.1	52.5	50.6	5.5	5.7
May	12.8	13.3	5.6	5.9	48.6	52.6	5.1	5.7
June	15.0	15.7	8.1	8.6	53.5	48.8	4.5	4.2
July	16.5	17.6	10.2	10.7	60.9	59.0	4.2	3.9
Aug	16.8	17.4	10.1	10.4	70.5	88.0	4.3	4.7
Sep	14.9	15.9	8.4	9.2	81.4	75.4	5.1	5.2
Oct	12.3	13.2	6.1	6.6	91.4	102.8	5.6	5.5
Nov	9.2	9.8	3.3	3.6	101.9	98.1	5.8	5.8
Dec	7.5	8.0	2.0	1.7	93.5	102.6	6.0	6.2
Annual	**11.4**	**12.2**	**5.1**	**5.6**	**877.4**	**922.8**	**5.4**	**5.5**

6.2.4 Hydrogeology

Surface hydrology

257 The Dounreay licensed site generally lies within the surface water catchment of the Dounreay Burn/Mill Lade, for which a considerable amount of data has been collected by DSRL (e.g. [227; 228]). However, the surface water catchment of the D3100 area lies to the north of the Dounreay Burn catchment. There is no single stream capturing the flow, and there is also an engineered drainage system underneath the runway that captures a considerable portion of surface flow. Figure 6.12 shows the natural surface water catchment surrounding D3100 defined on the basis of the natural topography [229; 230].

258 Prior to construction of D3100, a complex network existed of part natural and part man-made ditches that drained the waterlogged ground between the facilities and the coast (Figure 6.12). This network has been largely removed during construction and replaced with the enhanced geosphere. On closure, the enhanced geosphere layer will be integrated with the cap, and the water table will be below the ground surface and discharge will be generally immediately along the cliff tops or through the cliffs.

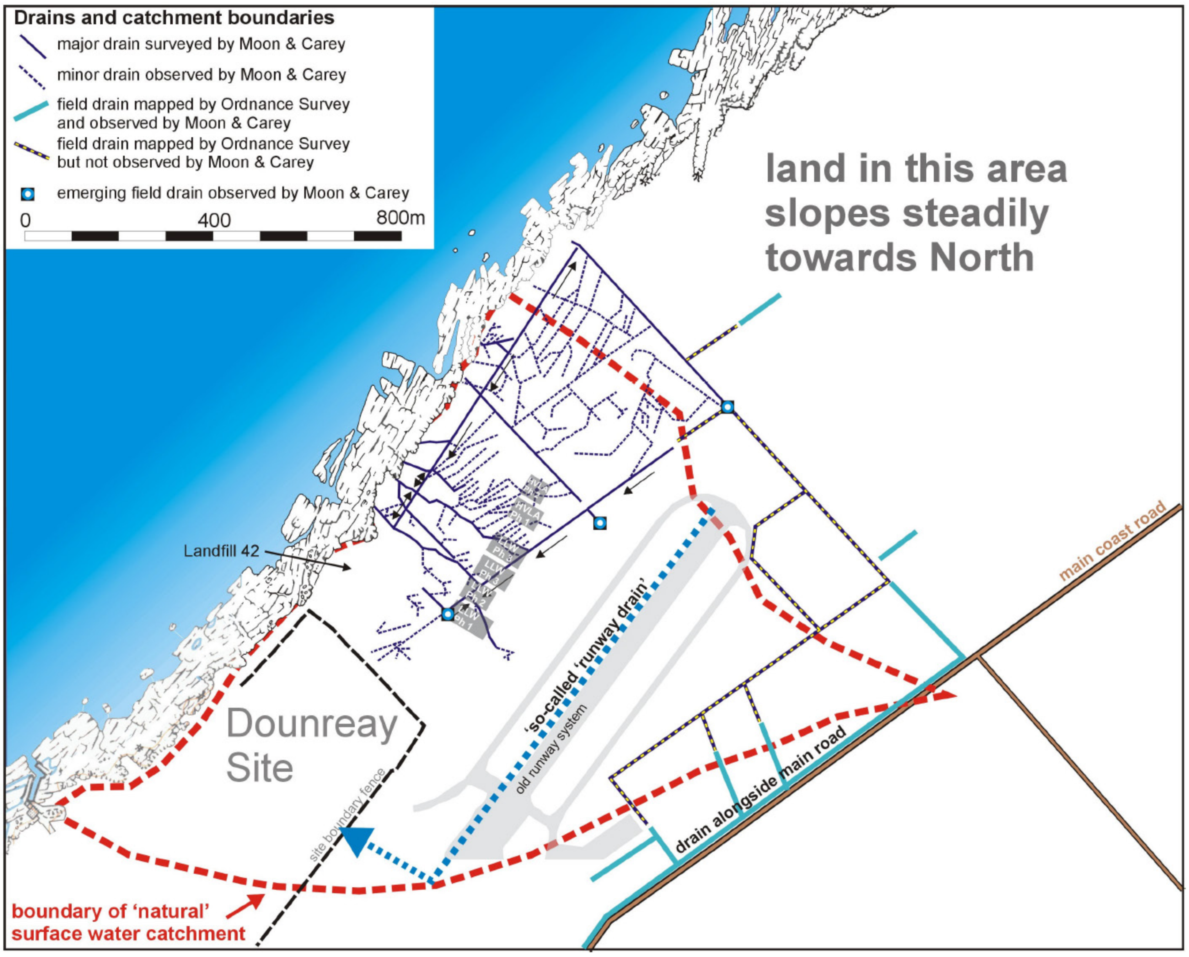

Figure 6.12: Map of the natural topographic boundary of the catchment containing the D3100 site prior to construction activities [230, Fig.3]. Reference to Moon & Carry in the key is referring to [205].

Subsurface hydrogeology

259 The conceptual hydrogeological model for the near-surface of the D3100 study area is shown in Figure 6.13 [229]. This illustrates the main hydrogeological units: a deeper groundwater system in an intact, low-permeability bedrock, overlain by a shallow or near-surface groundwater system in a more permeable weathered bedrock. Flow in unaltered bedrock is predominantly along fractures, the most prominent of which are the low-angle bedding planes dipping at around 10° to the north or northwest. There is no evidence from monitoring data for a north-northeast orientated flow of groundwater along potentially preferred pathways formed by local fault zones [231]. In the more permeable near-surface weathered zone, flow is probably more generally through the entire rock mass. However, the Quaternary cover shows considerable heterogeneity, and low-permeability zones and layers may locally affect flow patterns. In particular, clay-rich till layers may locally prevent vertical recharge and promote surface run-off of rainfall.

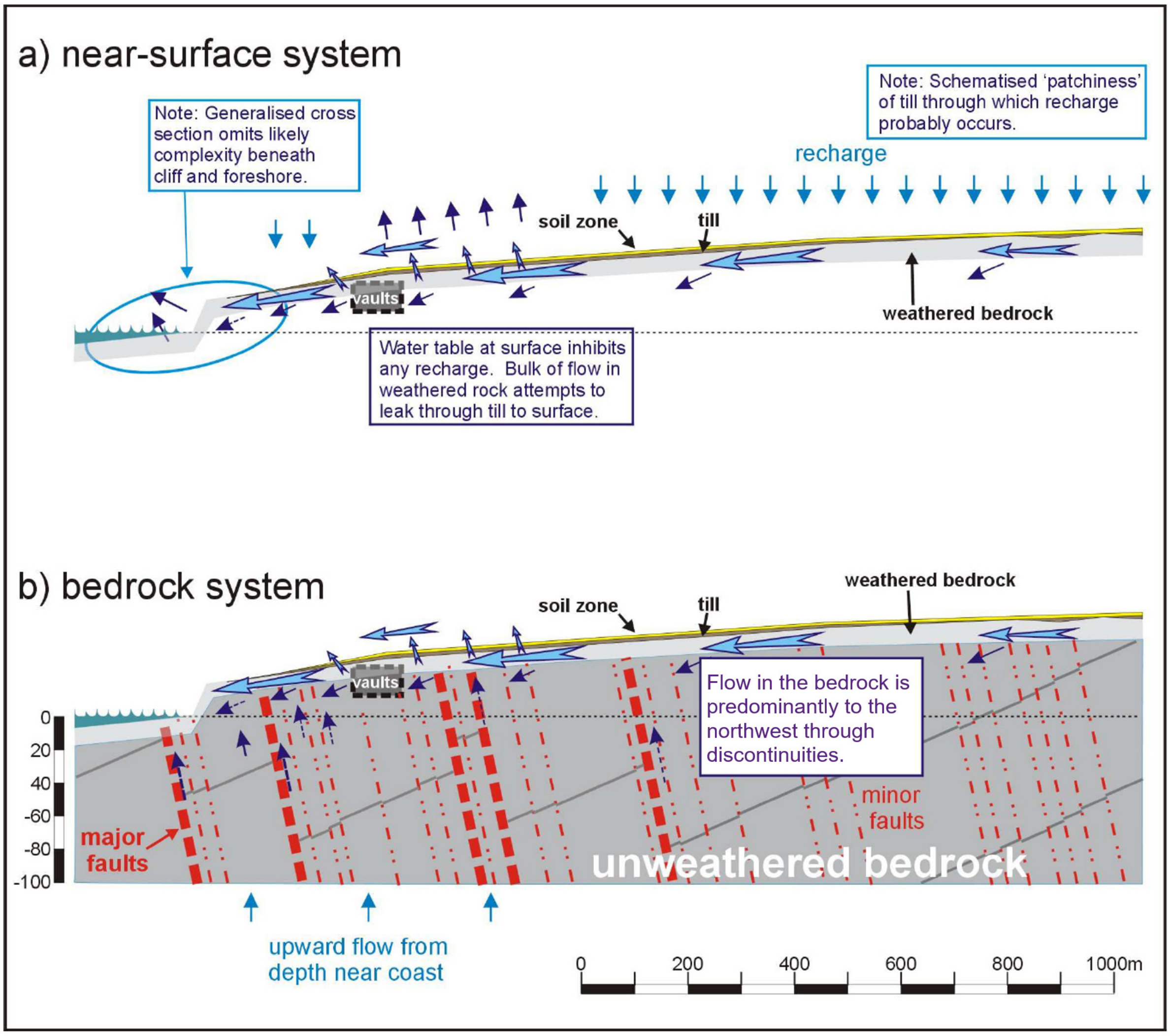

Figure 6.13: Conceptual hydrogeological model for the D3100 study area [after 229, Fig.35].

260 At depths below 100 m, upward gradients in boreholes on the Dounreay licensed site suggest that the Dounreay area is a location of regional discharge (Figure 6.13). This is supported by greater evidence of fresher water (i.e. not contaminated by sea-spray) at depth than near the surface. However, the influence of these deeper flow patterns on the behaviour of the shallower groundwater system of most relevance to D3100 is not considered to be high.

Hydraulic conductivities

261 Measurements of hydraulic conductivity in the MEX- (on the Dounreay site), LLW- and GW-series boreholes have been analysed to derive a profile of the variation of hydraulic conductivity with depth (Figure 6.14). All of the profiles shown are of the geometric mean of test results as this is considered to be a closer indicator of

large-scale permeability behaviour in the Devonian bedrock than the arithmetic mean[24].

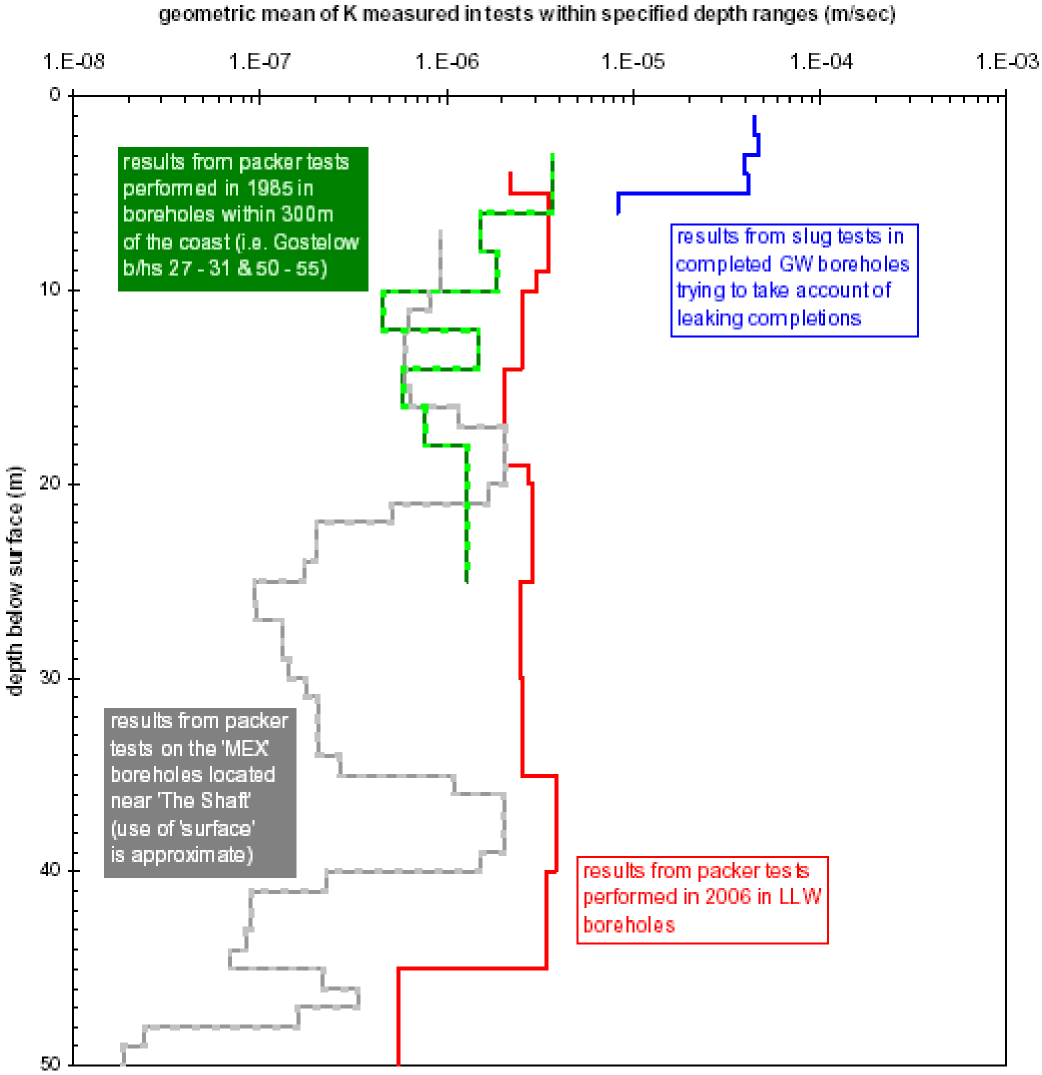

Figure 6.14: Depth profiles of hydraulic conductivity derived from tests in boreholes located in both the D3100 study area and the main Dounreay site [229, Fig.26].

262 Near to the ground surface, the GW-series borehole tests (blue line in Figure 6.14) yielded values that are generally more than an order of magnitude higher than the values obtained from the deeper LLW-series borehole tests. This appears to confirm that the weathered layer of bedrock is a zone of enhanced hydraulic conductivity compared to the deeper fresh bedrock. However, hydraulic conductivity drops rapidly a few metres below the surface to the values seen throughout the rest of the bedrock down to 50 m. This suggests that the hydraulic conductivity of the altered bedrock

24 The hydraulic conductivity values range over an order of magnitude or more, and the geometric mean is more representative of a large distribution of parameter values than the arithmetic mean, giving less bias to the high-end values of the distribution [229, §6.2].

layer below the weathered layer (Section 6.2.2; Figure 6.11) is not significantly different to that of the underlying fresh bedrock.

263 In the uppermost 20 m of the bedrock, hydraulic conductivity in the D3100 study area is only around half an order of magnitude greater than on the Dounreay site. Below 20 m, the difference seems to increase to about one order of magnitude, although more transmissive layers in the Shaft area approach the values seen in the D3100 study area. The higher measured hydraulic conductivities in the D3100 study area probably reflect the greater number of faults, and the associated fracturing at depth, compared to the Dounreay site, although the measurements in the D3100 study area may be biased towards higher values as the majority of the boreholes are located in highly faulted areas.

264 Measurements of hydraulic conductivity in the BM-series boreholes are generally slightly lower than the LLW-series values shown in Figure 6.14 and, while there is a slight decrease in bedrock conductivity with depth, there was insufficient distinction between zones for numerical groundwater local-scale modelling of the D3100 study area to consider both altered and weathered bedrock as distinct from the unaltered bedrock [200; 202]. This is consistent with paragraph 262 above and altered bedrock was not represented as separate to the unaltered bedrock in the hydrogeological modelling. Table 6.3 shows the hydrogeological units considered in the local-scale groundwater model, their average thickness based on interpretation of the geophysical survey, and the corresponding hydraulic conductivities measured in the BM-series boreholes. Table 6.3 also summarises the calibrated hydraulic conductivity (K) tensor for each finite element in the four main units in the 2012 Base Case model, and provides the K components along (K_x), across (K_y) and perpendicular (K_z) to bedding.

Table 6.3: Calibrated hydraulic conductivity (K) values for the major hydrogeological units identified for the D3100 study area [202].

Unit	Average thickness (m)	K used in 2012 Base Case (m s^{-1})	Measured K in BM boreholes (m s^{-1})*
Soil	0.3	K_x, K_y, K_z: 1.00E-04	-
Till	1.0	K_x, K_y: 7.10E-07 K_z: 3.60E-07	Average = 7.10E-07 Geometric mean = 3.60E-07
Weathered bedrock	3.4	K_x, K_y, K_z: 4.50E-06	Average = 4.50E-06 Geometric mean = 1.50E-06
Fresh bedrock	18.1	K_x, K_y: 1.10E-06 K_z: 1.10E-07	Average = 2.00E-06 Geometric mean = 1.10E-06

Groundwater Elevation

265 Groundwater elevations measured in 2009 [232], 2010 [233] and 2011 [234] define the pre-construction baseline conditions [235], and have a broadly similar pattern. Groundwater elevations were consistently near to, at, or above, ground level,

consistent with the current conceptual model (Figure 6.13). For the four geological units considered (superficial deposits, weathered bedrock, altered bedrock and unaltered bedrock), flow within all tended west-northwest towards the cliff line (e.g. Figure 6.15). The pre-construction baseline hydraulic gradient across most of the study area has been estimated at 0.037 (generally consistent with the topographic dip), decreasing slightly to 0.025 in the superficial deposits near the coast [235, ¶15].

266 Key findings from pre-construction groundwater elevation monitoring included:

- Groundwater was recharged by rainfall all year round [233, ¶126].
- Monitoring results suggested that seasonal variations in groundwater elevations appear to be typically less than 1 m [232, ¶38, Drawing 10; 233, ¶110; 234, ¶57, Drawing 11].
- Groundwater elevations indicated a slight westerly deflection in flow in all bedrock horizons towards the southwest of the site [232, ¶126; 233, ¶131; 234, ¶115]. This may reflect discharge to a drain close to Landfill 42.
- Small tidal responses of a few cm, recorded in groundwater elevation measurements collected within the unaltered bedrock, imply that such bedrock crops out in and below the intertidal zone, as depicted in the conceptual model [232, ¶71; 234, ¶59, Drawing 13].
- Detailed analysis of groundwater level monitoring data indicated variable directions of vertical hydraulic gradient locally [236; 234 ¶52 to 54]. Vertical hydraulic gradients within the weathered bedrock varied spatially and temporally across the site. Within the unaltered bedrock, vertical gradients were typically upwards except within boreholes close to the coast [232, ¶80; 234 ¶52 to 54]. Such observations are consistent with the conceptual model [236, p.3].

267 Groundwater elevations have greatly altered since the start of Phase 1 construction works. Pumping of groundwater flowing into the two excavation zones has occurred since 2012. Early on during Phase 1, pumping created a groundwater depression cone ca. 300 m across, with monitoring results suggesting it was slightly elongated in a northeast-southwest orientation [204]. More recent monitoring now shows that the depression cone has become elongated to the west-northwest-east-southeast (e.g. Figure 6.16) [237; Fig.3 to 5; 238, Fig.3 to 5]. The current long-axis direction is along the hydraulic gradient (towards the coast) and is likely influenced by the presence of the enhanced geosphere [239, ¶32].

268 After closure of D3100, groundwater elevations are expected to transition back towards levels similar to the pre-construction baseline. Figure 6.17 shows groundwater levels for the post-closure reference case developed in the local-scale hydrogeological model [202]. The elevated topography from the enhanced geosphere has created an unsaturated zone of ground between the vaults and the cliff-line. Groundwater flow results from the post-closure reference case [202] have been used to provide input for the Run 4 and 5 PA models. In addition, flow results from a variant, with lower hydraulic conductivity values assumed for the two lowest layers of the enhanced geosphere [202], have provided input for a highly pessimistic worst case scenario for the D3100 PA.

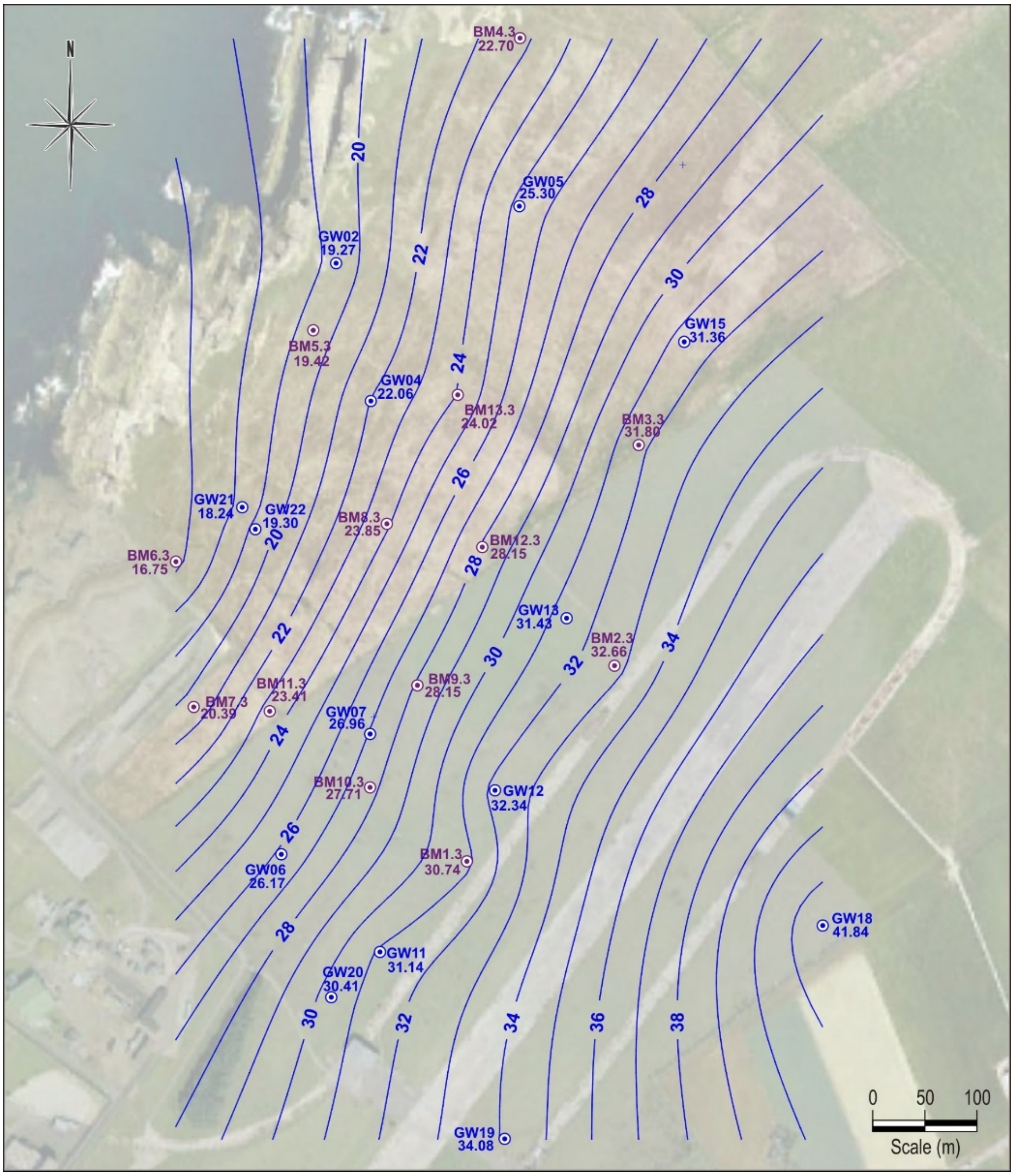

Figure 6.15: Contours of groundwater heads (levels) measured in weathered bedrock between 30/11/09 and 02/12/09 [232, Drawing 4], representative of baseline conditions prior to the start of Phase 1 construction.

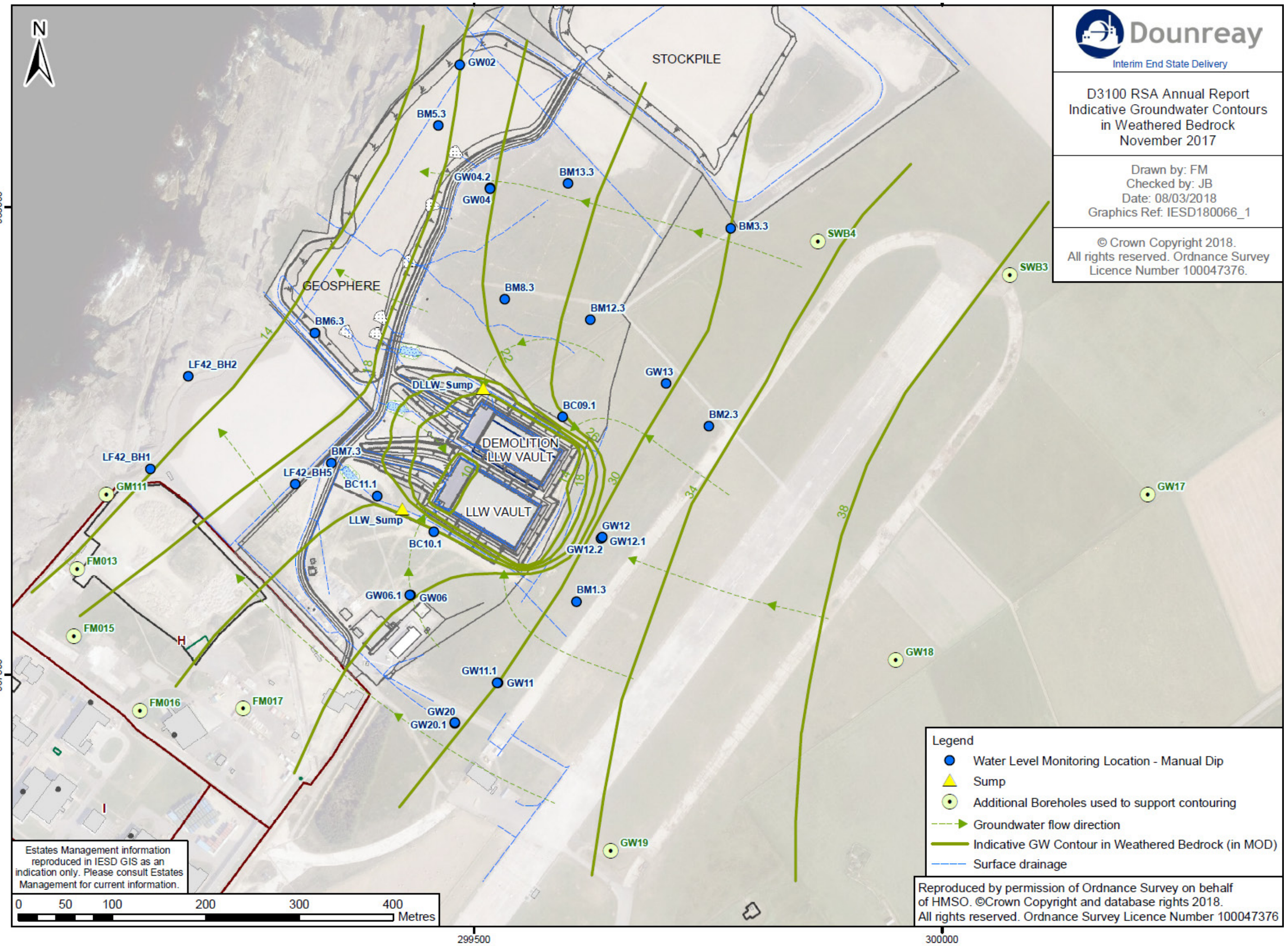

Figure 6.16: Contours of groundwater heads (m AOD) measured in weathered bedrock in November 2017 [238, Fig.4], representative of the conditions subsequent to Phase 1 construction and a period of re-settling.

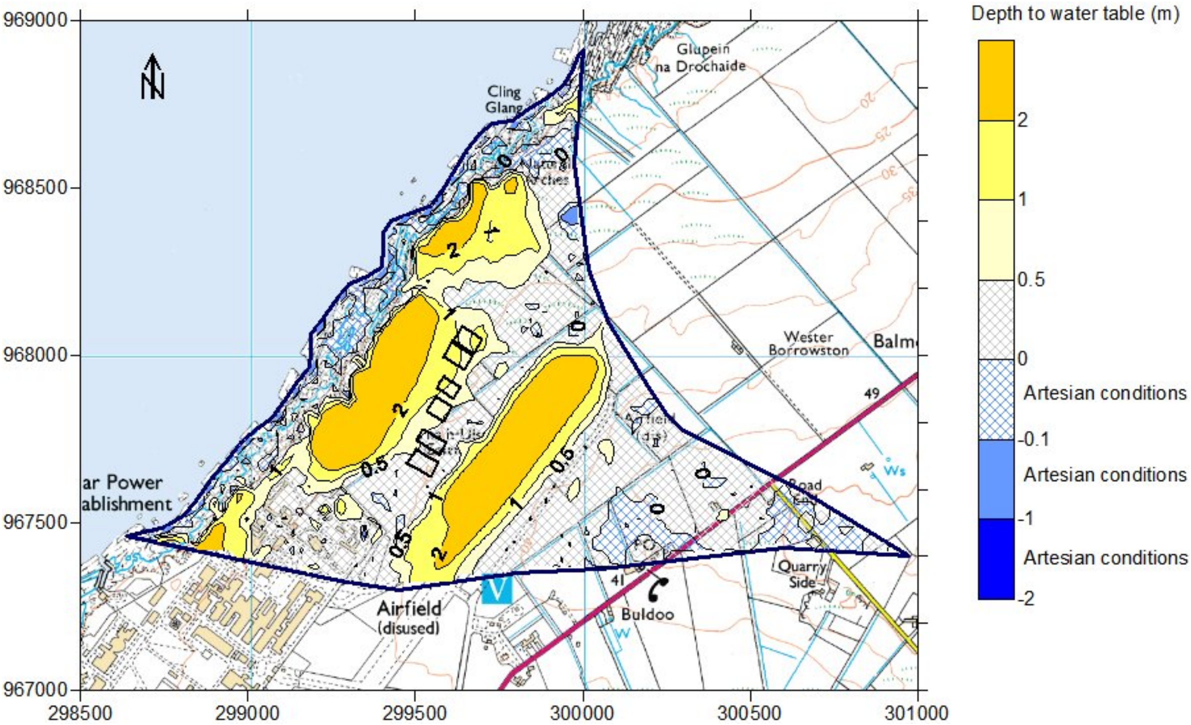

Figure 6.17: Contour maps of the depth to groundwater computed for the post-closure reference case model [202, Fig.3.6b]. Outline boxes show the indicative position the modelled vaults after closure.

6.2.5 Geochemistry

Baseline surface water chemistry

269 The major ion chemistry of surface water prior to Phase 1 construction was dominated by calcium, sodium, bicarbonate and chloride, and thus was chemically similar to that of the groundwater (see below), suggesting surface waters were likely partly composed (ca. 30 to 70%) of shallow groundwater [233, ¶126; 234, ¶138]. Sea spray influences calcium and chloride concentrations locally [233, ¶126; 234, ¶138].

270 With respect to minor ion chemistry, statistical comparison was undertaken between measurements collected in 2009, 2010 and 2011. There was no clear evidence for consistent increasing or decreasing trends in surface water minor ion concentrations [233, ¶127; 234, ¶139].

271 Organic substances were sporadically detected within surface water at concentrations close to detection limits. It has been proposed that such detections were likely an artefact of the laboratory testing [233, ¶128; 234, ¶151], though some of the organic substances (e.g. some of those encompassed in the label Total Petroleum Hydrocarbons [TPH]) may be of natural origin.

272 Radioactive substances were occasionally identified at low concentrations in surface waters; there was no trend showing increasing or decreasing concentrations over this time [233, ¶129; 234, ¶152].

273 Table 6.4, Table 6.5 and Table 6.6 present the minimum, maximum and mean concentrations of detected chemical determinands found in surface waters for the D3100 study area [235]. Only determinands with at least one detect over the monitoring period are shown. Further determinands to those listed were tested but were not detected [235, Tab.5.2].

Table 6.4: Summary of the D3100 baseline for non-organic determinands, in mg L^{-1} (unless otherwise stated), detected in pre-construction surface water [235, Tab.5.3].

Determinand	Min	Max	Mean	Stand. Dev.
Aluminium	1.00E-02	3.40E-01	6.72E-02	7.58E-02
Ammonia	1.21E-02	1.21E+00	5.98E-02	1.71E-01
Arsenic	1.00E-03	5.00E-02	2.17E-03	5.58E-03
Barium	5.00E-02	1.30E-01	7.51E-02	1.63E-02
Beryllium	1.00E-03	1.00E-02	9.65E-03	1.75E-03
Boron Water Soluble	1.00E-02	6.00E-02	2.49E-02	1.27E-02
Cadmium	1.00E-04	1.00E-03	1.56E-04	1.84E-04
Calcium	3.00E+01	8.30E+01	5.20E+01	1.04E+01
Chloride	4.20E+01	1.95E+02	8.14E+01	2.42E+01
Chromium	1.00E-03	6.00E-03	1.84E-03	1.17E-03
Chromium Hexavalent	5.00E-02	5.00E-02	5.00E-02	0.00E+00
Cobalt	1.00E-03	8.00E-03	1.22E-03	1.16E-03
Copper	1.00E-03	8.80E-02	4.55E-03	9.98E-03
Cyanide - Complex	5.00E-02	5.00E-02	5.00E-02	0.00E+00
Cyanide - Free	5.00E-02	5.00E-02	5.00E-02	0.00E+00
Ferric Iron (Fe III)	1.00E-02	7.00E-02	4.67E-02	3.21E-02
Ferrous Iron (Fe II)	1.00E-02	1.00E-02	1.00E-02	0.00E+00
Iron	1.00E-03	7.20E-01	1.14E-01	1.23E-01
Lead	1.00E-03	7.00E-03	1.18E-03	7.90E-04
Magnesium	1.10E+01	2.60E+01	1.77E+01	2.56E+00
Manganese	1.00E-03	8.97E-01	1.13E-01	1.76E-01
Mercury	1.00E-04	1.00E-03	1.38E-04	1.75E-04
Molybdenum	1.00E-04	7.00E-03	1.75E-03	1.30E-03
Nickel	1.00E-03	1.70E-02	3.42E-03	2.62E-03
Nitrate	2.00E-01	3.00E+00	4.78E-01	5.49E-01
Nitrite	1.00E-02	1.00E+00	3.83E-02	1.53E-01
Phosphate	1.00E-02	1.00E+00	9.95E-02	2.56E-01
Potassium	3.00E+00	1.60E+01	5.78E+00	2.49E+00
Selenium	1.00E-03	4.00E-03	1.16E-03	6.08E-04
Sodium	2.80E+01	1.58E+02	5.31E+01	1.55E+01
Sulphate	5.00E+00	6.60E+01	2.46E+01	8.78E+00
Sulphide	5.00E-02	3.40E-01	8.19E-02	6.96E-02

Determinand	Min	Max	Mean	Stand. Dev.
Tin	1.00E-03	7.00E-03	1.18E-03	9.84E-04
Total Cyanide	2.00E-02	2.80E-01	2.83E-02	4.05E-02
Vanadium	1.00E-03	2.00E-03	1.67E-03	5.77E-04
Zinc	2.00E-03	3.70E-02	4.74E-03	5.73E-03
Alkalinity	1.40E+02	2.30E+02	1.90E+02	4.58E+01
Chemical Oxygen Demand	1.20E+01	1.23E+02	2.35E+01	1.69E+01
Dissolved Oxygen	9.10E+00	9.20E+00	9.13E+00	5.77E-02
Electrical Conductivity (Lab) ‡	4.15E+02	1.15E+03	5.98E+02	9.63E+01
Suspended Solids	5.00E+00	3.97E+03	8.01E+01	4.53E+02
Total Acidity as $CaCO_3$	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total Alkalinity as $CaCO_3$	1.04E+02	2.67E+02	1.81E+02	3.52E+01
pH §	6.5	9	7.68	0.468

‡ units of μS/cm; § pH units of $-\log_{10}[H^+]$

Table 6.5: Summary of the D3100 baseline for organic determinands, in mg L^{-1}, detected in pre-construction surface water [235, Tab.5.4].

Determinand	Min	Max	Mean	Stand. Dev.
1_2_4-Trimethylbenzene	1.00E-03	2.00E-03	1.02E-03	1.51E-04
Acenaphthene	1.00E-05	2.00E-03	1.14E-04	4.41E-04
Acenaphthylene	1.00E-05	2.00E-03	1.18E-04	4.41E-04
Benz(a)anthracene (56-55-3)	1.00E-05	2.00E-03	1.14E-04	4.41E-04
Fluoranthene (206-44-0)	1.00E-05	2.00E-03	1.14E-04	4.41E-04
Fluorene (86-73-7)	1.00E-05	2.00E-03	1.14E-04	4.41E-04
Fraction Organic Carbon	1.00E-01	1.90E+01	6.40E+00	1.09E+01
Naphthalene	1.00E-05	2.73E-03	2.33E-04	5.77E-04
Polycyclic aromatic hydrocarbons, total US EPA 16	1.00E-04	5.00E-04	1.73E-04	7.30E-05
Phenanthrene (85-01-8)	1.00E-05	2.00E-03	1.16E-04	4.41E-04
Pyrene (129-00-0)	1.00E-05	2.00E-03	1.14E-04	4.41E-04
Total organic carbon	1.00E+00	2.60E+01	8.48E+00	3.83E+00
Total Petro. Hydrocarbons	1.00E-02	4.86E-01	4.07E-02	9.41E-02
TPH C10-C12 Aliphatic	5.00E-03	3.16E-01	1.39E-02	5.26E-02
TPH C12-C16 Aliphatic	1.00E-02	1.70E-01	1.46E-02	2.70E-02

Table 6.6: Summary of the D3100 baseline for radiological determinands, in Bq L^{-1}, detected in pre-construction surface water [235, Tab.5.5].

Determinand	Min	Max	Mean	Stand. Dev.
Bismuth-214	1.10E+00	2.90E+00	1.87E+00	9.29E-01
Gross Alpha Activity	4.70E-02	2.10E+00	1.88E-01	2.55E-01
Gross Beta Activity	1.60E-01	5.90E+00	5.10E-01	6.97E-01
Tritium-3	9.10E+00	1.00E+01	9.99E+00	1.05E-01

Baseline groundwater chemistry

274 Groundwater in the D3100 study area prior to Phase 1 was fresh (total dissolved solids < 1 g L^{-1}), of neutral pH, and contained calcium, sodium, bicarbonate and chloride as major ions [240]. There was little temporal change in water quality. Moving down hydraulic gradient towards the cliffs there was a spatial trend in percentage increases in sodium and potassium in groundwater relative to calcium [232, ¶42]. A concomitant spatial trend was observed for chloride in groundwater, which became increasingly dominant over the other anions towards the coast. Where increasing salinity was recorded it has been attributed to the mixing of groundwater with seawater from marine spray and, to a lesser extent, due to groundwater interaction with the host rocks (ion exchange, carbonate mineral dissolution) [233, ¶120; 240, p.1].

275 Detailed characterisation of the major ion chemistry for groundwater in the D3100 study area confirmed the importance of mixing of sodium chloride dominated “saline” water of marine aerosol origin with calcium bicarbonate dominated “fresh” groundwater [241]. The more saline groundwater was observed at down-gradient boreholes, with the effect reducing with depth. However, it has also been possible to discriminate other processes, namely cation exchange and calcite dissolution [233, ¶72 and 73; 234, ¶63 and 64]. The effect of calcium being exchanged by sodium in the groundwater was most apparent at down-gradient locations in all rock horizons, and resulted in a decrease in calcium and an increase in sodium concentrations [241]. The process of calcite dissolution was more important at up- and mid-gradient locations [233, ¶74; 234, ¶65], increasing calcium concentrations in groundwater. Calcite dissolution tended to increase with depth and was more variable in the weathered bedrock, reflecting variability in the pCO_2 [241].

276 The concentrations of minor and trace elements such as arsenic, cadmium, mercury and uranium in the groundwater are considered to be the result of natural occurrences in the ground [232, ¶105; 233, ¶125]. Statistical comparisons were undertaken between measurements collected in 2009, 2010 and 2011 on concentrations of minor ions. No clear increasing or decreasing trends in the groundwater minor ion chemistry between the datasets or changes in groundwater quality were found [233, ¶123; 234, ¶129].

277 Mineralogical and thermodynamic data suggested that the groundwater redox conditions were reducing at relatively shallow depths (a few metres below the surface) [233, ¶39]. Reducing conditions were corroborated by groundwater monitoring data, which indicated low dissolved oxygen levels and redox potential

readings typically around -200 mV [242]. The iron and manganese contents of groundwater were much higher than in surface water, as would be expected from the reducing conditions [242; 233, ¶39]. In addition, sulphate reducing conditions existed in the deeper bedrock, consistent with low redox potential [233, ¶39].

278 Near-surface reducing conditions are consistent with observations that iron-staining of fractures was not seen in core samples at depths greater than 6.5 m [243, p.7], and suggests that recharge in the D3100 study area was limited in penetration to the near-surface groundwater layer within the weathered bedrock (Section 6.2.2).

279 A detailed examination of the spatial distributions of different redox indicators (redox potential, dissolved oxygen, iron, manganese, nitrate/nitrite and sulphate/sulphide) in the groundwaters of the study area concluded that the groundwater across nearly the entire area was reducing [244, p.3]. The weathered bedrock appeared to be less reducing than the deeper bedrock, and contained dissolved oxygen, probably introduced by water infiltrating through the overlying till [244, p.3]. In contrast, dissolved oxygen could not be detected (limit of detection 0.01 mg L^{-1}) in groundwaters from altered and unaltered bedrock [244, p.2].

280 As with surface waters, organic substances were sporadically detected within groundwater at concentrations close to detection limits. Again, it has been proposed that such detections were likely an artefact of laboratory testing [234, ¶136].

281 Gross alpha and gross beta activities were detected in groundwater samples (e.g. [232, ¶118; 234, ¶87-88]). It is believed that most of this activity derives from natural sources [232, ¶118]. Groundwater samples from some of the BM-series boreholes were analysed for mass concentrations of ^{235}U and ^{238}U [232, Tab.3; 233, Tab.6; 234, Tab.8]. The ^{235}U / ^{238}U mass ratio values were consistent with the detected uranium coming from natural sources [232, ¶104; 234, ¶125].

282 Table 6.7, Table 6.8 and Table 6.9 present the minimum, maximum and mean concentrations of detected chemical determinands found in groundwaters for the D3100 study area [235]. Only determinands with at least one detect over the monitoring period are shown. Further determinands to those listed were tested but were not detected [235, Tab.4.2].

Table 6.7: Summary of the D3100 baseline for non-organic determinands, in mg L^{-1} (unless otherwise stated), detected in pre-construction groundwater [235, Tab.4.3].

Determinand	Min	Max	Mean	Stand. Dev.
Aluminium	1.50E-03	8.25E+00	6.95E-02	4.88E-01
Ammonia	1.21E-02	5.10E+00	2.66E-01	6.88E-01
Arsenic	2.00E-04	1.61E-01	9.86E-03	1.59E-02
Barium	1.80E-03	1.04E+00	2.60E-01	1.91E-01
Boron Water Soluble	2.00E-03	3.93E-01	4.77E-02	4.01E-02
Cadmium	2.00E-05	1.36E-02	2.09E-04	8.84E-04
Calcium	1.04E-01	1.32E+02	9.02E+01	2.13E+01
Chloride	5.50E+01	7.42E+02	1.65E+02	1.15E+02
Chromium	2.00E-04	5.00E-01	4.94E-03	2.98E-02
Cobalt	1.00E-04	1.00E-02	1.94E-03	2.17E-03

Determinand	Min	Max	Mean	Stand. Dev.
Copper	5.00E-04	2.70E-02	2.26E-03	3.25E-03
Fluoride	9.00E-02	1.00E+00	3.84E-01	4.03E-01
Iron	4.70E-03	2.55E+01	1.44E+00	3.15E+00
Lead	3.00E-04	6.10E-02	2.05E-03	5.38E-03
Magnesium	7.00E+00	5.20E+01	2.92E+01	7.70E+00
Manganese	1.50E-03	6.09E+00	5.51E-01	9.65E-01
Mercury	5.00E-05	4.00E-03	1.52E-04	2.87E-04
Molybdenum	1.00E-04	2.50E-02	3.31E-03	3.59E-03
Nickel	2.00E-04	2.00E+00	1.05E-02	1.16E-01
Nitrate	5.00E-02	4.03E+01	4.95E-01	2.70E+00
Nitrite	6.00E-03	1.50E+00	3.06E-02	1.44E-01
Phosphate	1.00E-02	1.76E+00	6.52E-02	2.29E-01
Potassium	2.00E+00	1.70E+01	4.60E+00	2.93E+00
Selenium	1.00E-03	7.00E-03	1.42E-03	8.58E-04
Silicon	6.00E+00	8.00E+00	7.25E+00	7.07E-01
Sodium	1.70E-01	4.20E+02	1.02E+02	7.80E+01
Sulphate	4.00E+00	9.40E+01	2.89E+01	1.57E+01
Sulphide	1.00E-02	1.60E+00	1.00E-01	1.33E-01
Tin	1.00E-03	5.00E-02	5.80E-03	6.19E-03
Zinc	1.50E-03	1.10E-01	5.81E-03	1.04E-02
Chemical Oxygen Demand	5.00E+00	9.10E+01	1.46E+01	1.28E+01
Electrical Conductivity	3.14E+02	2.67E+03	1.06E+03	4.08E+02
Suspended Solids	1.00E+00	2.04E+04	1.78E+02	1.30E+03
Total Acidity as $CaCO_3$	0.00E+00	4.00E+00	1.44E-02	2.40E-01
Total Alkalinity as $CaCO_3$	4.30E+01	6.00E+02	2.95E+02	7.85E+01
pH §	6.3	8.37	7.08	0.337

‡ units of µS/cm; § pH units of $-\log_{10}[H^+]$

Table 6.8: Summary of the D3100 baseline for organic determinands, in mg L^{-1}, detected in pre-construction groundwater [235, Tab.4.4].

Determinand	Min	Max	Mean	Stand. Dev.
1_1-Dichloroethane	1.00E-03	1.00E-02	1.24E-03	9.01E-04
Acenaphthene	1.00E-05	1.00E-02	2.68E-04	9.67E-04
Acenaphthylene	1.00E-05	1.00E-02	2.69E-04	9.67E-04
Anthracene	1.00E-05	1.00E-02	2.67E-04	9.67E-04
Benz(a)anthracene	1.00E-05	1.00E-02	2.97E-04	1.11E-03
Benzo(a)pyrene	1.00E-05	1.00E-02	2.67E-04	9.67E-04
Benzo(b/k) Fluoranthene	1.00E-05	1.00E-02	2.18E-04	1.41E-03
Benzo(ghi)perylene	1.00E-05	1.00E-02	2.67E-04	9.67E-04
Bis (2-ethylhexyl)phthalate	1.00E-03	3.80E-02	6.46E-03	3.92E-03
Chrysene	1.00E-05	1.00E-02	2.67E-04	9.67E-04

Determinand	Min	Max	Mean	Stand. Dev.
Di-n-butylphthalate	1.00E-03	1.00E-02	5.43E-03	1.49E-03
Dibenz(ah)anthracene	1.00E-05	1.00E-02	2.67E-04	9.67E-04
Fluoranthene	1.00E-05	1.00E-02	2.97E-04	1.11E-03
Fluorene	1.00E-05	1.00E-02	2.67E-04	9.67E-04
Indenopyrene	1.00E-05	1.00E-02	2.67E-04	9.67E-04
Naphthalene	1.00E-05	1.00E-02	5.09E-04	1.13E-03
Polycyclic aromatic hydrocarbons, total	1.00E-05	2.00E-02	2.42E-04	1.23E-03
Phenanthrene	1.00E-05	1.00E-02	2.67E-04	9.67E-04
Pyrene	1.00E-05	1.00E-02	2.98E-04	1.11E-03
Total organic carbon	1.40E+00	3.70E+01	6.39E+00	4.92E+00
Total Petro. Hydrocarbons	1.00E-02	1.38E+00	8.68E-02	1.70E-01

Table 6.9: Summary of the D3100 baseline for radiological determinands, in Bq L^{-1}, detected in pre-construction groundwater [235, Tab.4.5].

Determinand	Min	Max	Mean	Stand. Dev.
Bismuth-212	1.17E+00	2.65E+00	1.63E+00	4.07E-01
Caesium-137	5.46E-02	2.60E+00	2.35E-01	1.89E-01
Curium 243/244	6.90E-05	1.58E-03	5.32E-04	5.42E-04
Gross Alpha Activity	5.00E-02	1.80E+01	5.69E-01	1.27E+00
Gross Beta Activity	9.30E-02	4.70E+01	1.09E+00	3.90E+00
Lead-212	1.54E-01	1.22E+00	4.17E-01	2.88E-01
Lead-214	2.45E-01	5.58E-01	3.31E-01	1.08E-01
Plutonium-238	1.00E-03	3.00E-02	7.35E-03	6.99E-03
Plutonium-239 + 240	2.80E-04	1.90E-02	4.85E-03	3.87E-03
Strontium-90	8.30E-03	1.80E-01	5.53E-02	3.94E-02
Thallium-208	1.02E-01	3.82E-01	1.86E-01	1.09E-01
Thorium-232	1.73E-01	5.63E-01	2.73E-01	1.36E-01
Tritium-3	1.80E+00	1.70E+01	9.55E+00	1.89E+00
Uranium-234	4.60E-03	3.40E-01	8.21E-02	9.07E-02
Uranium-235 (alpha spec)	3.70E-04	2.00E-02	7.01E-03	6.05E-03
Uranium-238	3.17E-03	4.30E-01	7.98E-02	1.10E-01

Changes in water chemistry since Phase 1 construction

283 Prior to the start of Phase 1, geochemical modelling was undertaken to predict the changes in the baseline water chemistry resulting from the excavations [245]. Key conclusions of this work were that:

- pH values could marginally increase;

- electrical conductivity values could decrease;
- redox conditions could become increasingly more oxidising;
- groundwater could become supersaturated with respect to oxides;
- calcite could be expected to precipitate from solution; and
- evidence of sea spray in coastal boreholes would continue to be recorded.

284 These conclusions have been considered during water monitoring rounds subsequent to the start of Phase 1, as well as reviewed in the D3100 Monitoring Programme Evaluation [239]. The geochemical modelling is also currently being reviewed as part of ongoing site characterisation (Section 6.4).

285 Slight increases in pH have been recorded in two boreholes (BM1.1 and BM6.1) since the start of Phase 1 [239, Fig.3.1]. However, increases are less than predicted in [245].

286 Slight increases in electrical conductivity values have been recorded in groundwater since the start of Phase 1 [239, Fig.3.2; 238, ¶116]. This is counter to what was predicted in [245]. This is likely a result of an increase in the concentrations of major ions such as chloride and sodium whilst the concentrations of calcium and carbonate, which were predicted to decline, have remained relatively level [239, ¶77].

287 Since the start of Phase 1, there has been a large increase in the sulphate content of groundwater [239, Fig.3.4; 238, ¶118], likely reflecting oxidation of sulphide, perhaps leached from pyrite in the bedrock [239, ¶80]. The calculated saturation indices for iron sulphide minerals (e.g. mackinawite) are close to zero, consistent with the gradual destabilisation of pyrite [239, ¶80].

288 The main mineral oxide phases predicted to precipitate in the modelling report [245] are ferrihydrite, goethite and manganite. Precipitation of these minerals should result in a loss of dissolved iron and manganese from the groundwater. However, there has been no marked change over time in dissolved iron and manganese concentrations in the deep groundwater samples considered in [239, ¶81]. Concentrations of dissolved iron are greatest up-gradient [238, ¶121]. This is consistent with the prediction in the modelling report that up-gradient groundwater will exhibit the highest concentrations, owing to ongoing oxidation and precipitation of iron (III) oxides as the groundwater flows downstream past/into the excavations [239, ¶81].

289 The modelling report [245] predicts that calcite will be the most precipitated mineral phase in terms of mass during equilibration with air. Precipitation of calcite should be manifested by a decrease in pCO_2, a loss of dissolved calcium and a decrease in alkalinity in the groundwater. However, such trends have not yet been recorded to the degree initially expected [239, ¶83]. Therefore, the amount of calcite precipitation predicted in the modelling report will not have occurred.

290 A 2020 study noted precipitation build-up on excavation walls and in drainage channels at the base of the excavations (Figure 6.18) [246]. A chemical analysis of the precipitates from these two areas identified that they are predominantly made up of iron hydroxides (e.g. goethite) and calcite, respectively [246, §3.3]; this is in agreement with the precipitate phases predicted by the geochemical model.

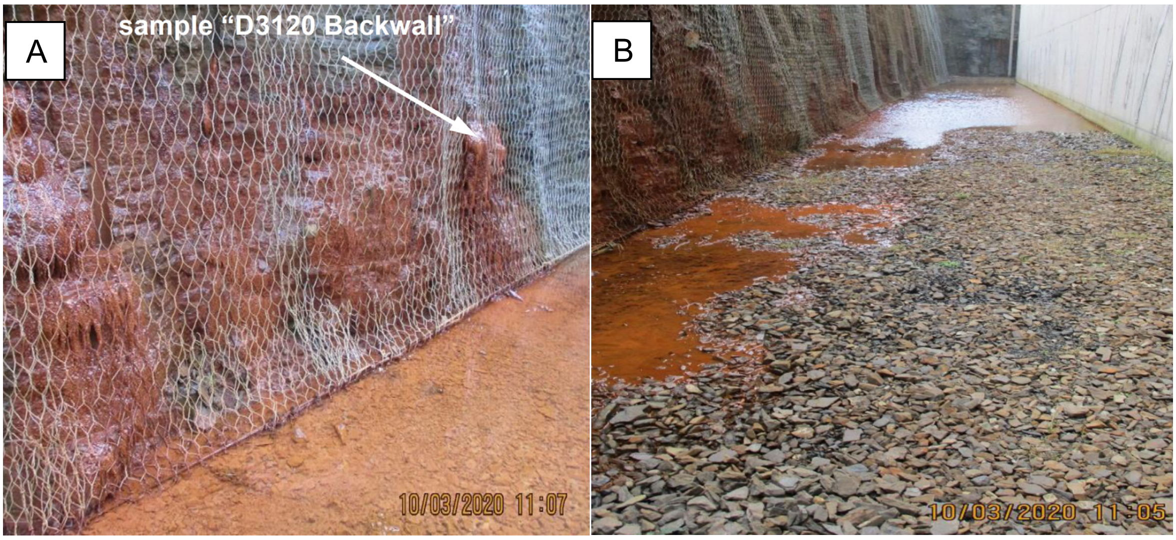

Figure 6.18: Photographs of the accumulation of mineral precipitates on wall excavations (A) and the lower drainage channel (B) of D3120 (LLW-1) [246, Fig.5 and 6].

291 Chloride concentrations in boreholes have been found to vary [239, Fig.3.7], decreasing and increasing locally. It is proposed that the effect of sea spray, and thus chloride concentrations, is influenced by factors local to the boreholes. Reductions could relate to the addition of enhanced geosphere over a borehole, reducing the effect of sea spray [239, ¶84]. For boreholes in close proximity to the vaults, sea spray and rain falling directly into the excavations and then entering the deep groundwater may explain the slight increase recorded [239, ¶84]. A second explanation could be that higher values relate to road grit laid down in winter on the roads across the D3100 site.

292 In regards to other aspects of water chemistry at the D3100 site, such as radioactivity levels, major and minor ion concentrations (apart from those discussed above) and organic contaminant concentrations, no largescale changes from the baseline water quality conditions have been recorded (e.g. [204, p.20-21; 237, §8.2; 238, §8.2]).

Soil/Rock contamination

293 During the surface survey to establish baseline radioactivity levels for the D3100 study area [247], 17 areas were identified as containing elevated levels of ^{137}Cs and a single gamma-producing particle was detected and retrieved by DSRL. The survey resulted in five radiological areas of interest being identified across the D3100 site. The single particle was most likely windblown from the sea, from the surface of Landfill 42 or from the Dounreay site [248, p.7]. Contamination that was identified was consistent with contamination from Dounreay discharges as well as fallout from weapons-testing and Chernobyl washing off and collecting at the edge of the Dounreay runway [248, p.11].

294 Radiological analysis of soils and borehole core samples from the D3100 study area has also been undertaken to determine background radioactivity levels and support an assessment of potential contamination. Arithmetic mean values for gross alpha and gross beta/gamma activity in the main geological units from the study area are

shown in Table 6.10. The gross alpha and beta/gamma activity levels for soils from the study area are lower than estimates for the Dounreay licensed site soils [50]. Radioactivity levels in the bedrock are variable, with localised elevations of radioactivity possible where natural uranium is present in minerals, such as phosphates in the fossil fish beds or natural hydrocarbon material. Although there are few data for fault gouge, the fault gouge material also appears to contain elevated levels of gross alpha radioactivity. This may be related to the clay minerals present within fault gouges.

Table 6.10: Average radioactivity levels in soils and rocks of the D3100 study area [50].

Material	^{226}Ra (Bq g^{-1})	Gross α (Bq g^{-1})	Gross β/γ (Bq g^{-1})
Soils	0.061 (n = 40)*	0.667 (n = 52)	1.15 (n = 52)
Till	0.068 (n = 12)	0.88 (n = 12)	2.11 (n = 12)
Weathered Bedrock	0.054 (n = 4)	0.86 (n = 4)	2.71 (n = 4)
Fault Gouge	0.17 (n = 3)	1.89 (n = 3)	2.9 (n = 3)

* n is the number of samples.

295 In regards to non-radiological contamination, soil samples from around two rubble drain outfalls in the D3100 area have been collected and tested for organics and metals. Where organic and metal determinands were identified at relatively high concentrations, it was concluded that they were likely of natural origin [213]. In addition, site investigation works carried out on the made ground adjacent to the disused runway to the south of the site found a small amount of asbestos sheeting. It is believed that there is potential for further pieces of asbestos to be present within the made ground; however, no construction activities related to D3100 are planned at locations that may contain asbestos contamination [249, ¶83].

Retardation properties

296 Reviews of retardation or sorption behaviour for key radionuclides at Dounreay are presented in [250] and [251], and recommendations for safety assessment modelling are presented in [251], building on recommendations presented in [190].

297 A few experimental studies of sorption to Dounreay lithologies have been undertaken:

- Preliminary measurements of actinide sorption to Caithness flagstones were undertaken by Nirex, although there is uncertainty as to the relationship of the rock samples on which the measurements were made to the lithofacies identified in the bedrock. See Table 3 of [251] for a summary.
- Further scoping measurements of sorption to Devonian lithologies were undertaken for the D3100 project [216]. These measurements were carried out for the radionuclides in the LLW inventory identified as potentially significant to calculated dose/risk and most sensitive to retardation (strontium, uranium(VI), radium, niobium, plutonium(IV), and lead). The measurements were made using several rock core samples covering lithofacies A to D extracted from boreholes drilled in the area of interest. Although the measurements were made on powdered rock and the results

must be treated with caution, plutonium, lead and niobium sorbed strongly on all four lithofacies studied, while uranium and strontium sorbed relatively weakly.

- Towler (reported in [251, §4.2.3]) quoted *in situ* R_d values for caesium-contaminated soils adjacent to "Manhole 2" near the Castlegate Drain at Dounreay in the range 0.32 to > 1.6 m^3 kg^{-1}. No mineralogical or compositional data were presented for the soil samples.

298 There are several problems associated with applying the above sets of site-specific sorption data in safety assessment (PA) modelling:

- There is a potentially wide range of lithologies and minerals that radionuclides might contact during geosphere transport at Dounreay, making it difficult to select one or two sets of properties for an assessment model.
- Flow and radionuclide transport are predominantly along fractures in the Devonian bedrock (see Section 6.2.4). Therefore, the sorption properties of minerals lining the fractures are likely to be more appropriate for modelling, rather than the properties of the bulk Devonian lithologies themselves.
- Assessment models tend to use a single empirical parameter to represent sorption (the K_d value). This approach is limited in that it does not take into account the nature of different retardation mechanisms operating (e.g. ion-exchange, co-precipitation) or their different degrees of reversibility. For example, caesium sorption is likely to be by cation exchange and be independent of concentration, unlike behaviour in the K_d concept.
- K_d values measured on crushed rock under laboratory conditions are unlikely to reflect *in situ* conditions, and expensive laboratory procedures might be needed to reproduce key conditions. For example, the scoping study [216] experienced difficulty reproducing the carbon chemistry in the Dounreay groundwaters, and these difficulties may have affected the uranium measurements.

299 All assessment programmes face the same issues when deciding on what data to use in representing retardation: how reliably/reasonably can the data be adjusted to represent the site-specific modelling conditions and how important are the data to the safety case. These two issues need to be balanced with consideration of the assessment context, available resources, time, and the likely benefit/success of further laboratory measurement, field investigation and detailed modelling to fill gaps.

300 To-date, assessments at Dounreay have been supported by geosphere sorption databases based mainly on expert review of the scientific literature informed where appropriate by limited site-specific measurements (e.g. [251]). Given the problems listed above with deriving meaningful experimental data and the use of sensitivity analyses and data ranges in the Dounreay PAs to bound the uncertainties, this position is currently considered appropriate for the D3100 PA. Further confidence in the modelling of sorption in the geosphere is provided at Dounreay by characterisation of the migration of key radionuclides from existing disposals such as the LLW Pits and the Shaft – this is discussed further below.

301 Confidence in the K_d approach is provided by studies of observed radionuclide migration in bedrock around the Dounreay Shaft [252] and LLW Pits [253]. The study of radionuclide migration from the Shaft concluded that ^{90}Sr was more mobile than ^{137}Cs and $^{238/239}Pu$ [252], which is in keeping with the relative order of K_d values used in the D3100 PA. Leachate and groundwater information with respect to the LLW Pits suggests that the relative mobility of key radionuclides can be summarised as follows [253, §6.6]:

- High mobility – tritium, strontium, uranium.
- Low mobility – caesium, plutonium, americium.

302 This relative order is broadly consistent with the K_d values used in the D3100 PA; however, the K_d model of reversible sorption might not be appropriate for caesium. Caesium has been noted to sorb irreversibly on mica [250], and this irreversible process was modelled in [252] and the Shaft PA [254]. However, ^{137}Cs is not a key radionuclide in terms of calculated dose for the groundwater pathway considered in the D3100 PA (see Section 7) and so treating the sorption as reversible for D3100 is a conservative but reasonable simplification.

303 Radioactive contamination around the Shaft was assessed on the basis of a large number of rock core samples recovered during the emplacement of the Shaft Hydraulic Isolation Barrier [255]. The data from the cores were correlated to a variety of observed features such as stratigraphy, fracture orientation, iron staining and apparent mineralogy. The results confirm the dominance of fracture features and clay-rich mineralogy in hosting contamination, while indicating that iron staining and mineral infill/alteration products are less important. Radioactive contamination was commonly found to penetrate beyond the fracture surfaces on a centimetre scale, suggesting that contaminated groundwater was interacting with greater volumes of rock than that presented by the fracture faces alone.

304 These results led to an updated conceptual model of water flow, diffusion and sorption along discontinuities within the bedrock at Dounreay [252]. Contaminants are envisaged to diffuse in and out of higher porosity zones of alteration (see Section 6.2.2) that surround each discontinuity (Figure 6.19). It has been shown that adoption of this conceptual model and using a K_d approach to represent the sorption process produces a good fit to the field data, increasing confidence in the use of this approach in larger-scale PA modelling [252].

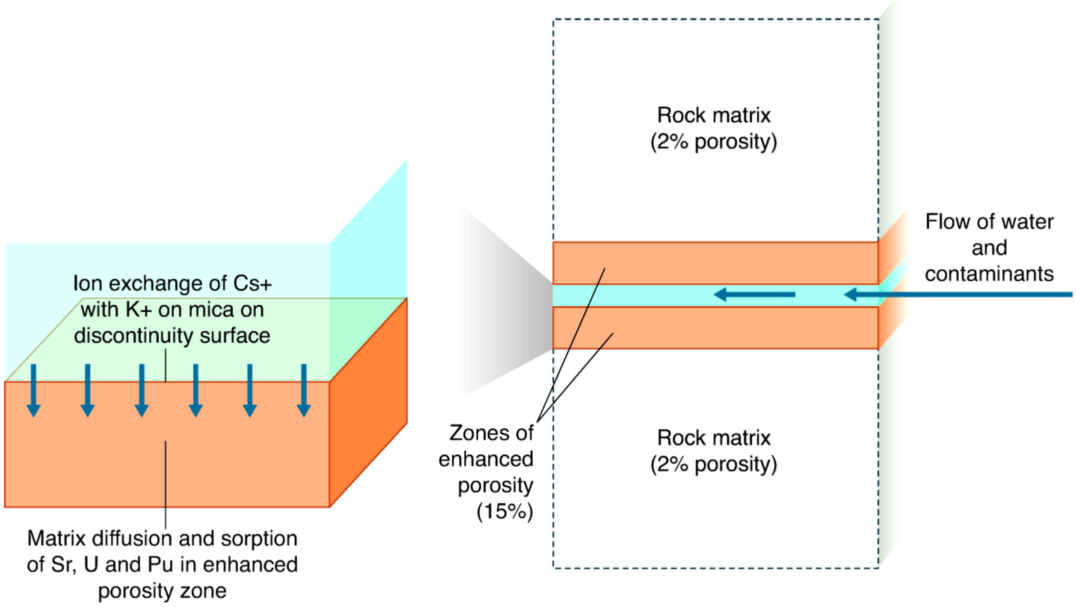

Figure 6.19: Conceptual model of water flow, diffusion, and sorption along discontinuities in the Dounreay Shore formation around the Shaft [252].

305 The conceptual model shown in Figure 6.19 and the K_d approach to representing radionuclide retardation has been adopted in the D3100 project PA discussed in Section 7. Selection of the K_d values is discussed in [50, Tab.4.2]. Sensitivity to the potential range of K_d values is examined in the D3100 PA.

6.2.6 Resource potential

306 Information on the presence of any actual or potentially valuable resources in the vicinity of D3100 is provided in [50]. There are no resources that present a strong driver for exploitation in the vicinity of D3100.

307 The Middle Devonian rocks that underlie the Dounreay site have been exploited elsewhere in the region for flagstones. However, this resource is plentiful and thus there is no reason to suggest the D3100 area might be excavated compared to any other area. Uranium mineralisation has been observed locally, but only at relatively minor concentrations. Past working of hematite veins at Achavarasdal, near Reay, and regional extractions of lead, zinc and copper have been noted [256].

308 Hydrocarbons, derived from organic material in the Devonian sediments, are found in the Devonian rocks [257] and associated with uranium mineralisation in the fracture systems. However, the majority of occurrences are on a scale of millimetres, and the Devonian rocks do not represent a potential economic resource for conventional hydrocarbons.

309 The volume of surface and near-surface water and the high precipitation of the region preclude the need to use the deeper groundwater for domestic and agricultural use. There are no obvious local geological features at depths equivalent to D3100 (i.e. less than 25 m) at the site that suggest the bedrock is likely to be chosen as a location to exploit groundwater resources in the event that significant quantities of

water are needed. Springs have been exploited locally for watering livestock, but these are fed by water from the near-surface flow system, rather than the deeper groundwater system in the unweathered bedrock.

6.3 Potential for Future Disruption of the Site

GRA 6.4.8(b)	Assess the potential for, and effects of, dynamic processes such as seismic events and ground subsidence.

310 Based on the scenario development process for the D3100 project PA described in Section 7, the key natural events and processes that could lead to disruption of the facilities at some point in the future are:

- changes in relative sea-level or flooding caused by a tsunami;
- coastal erosion (which may be exacerbated or eased by sea-level rise);
- seismic activity; and
- glacial erosion.

6.3.1 Marine flooding

Storm surge

311 No man-made flood protection has been constructed at the D3100 site to protect against the risk of present-day marine flooding. Such protection is not required due to the elevation above sea level and the natural protection provided by the ca. 10 – 15 m AOD coastal cliffs. The height of a 1-in-1000-year storm surge flood has been calculated to be 7.9 m AOD [258, p.199], much below the cliff height. Wave break heights on the shore to the northwest of the D3100 site have been estimated to be up to 14.5 m AOD [259, p.251]. However, such large waves would break some distance from the coastline (ca. 500 – 600 m, based on empirical relationships), and therefore much of the potential for mechanical action would have been reduced by the time the waves reached the cliffs [153, ¶29]. No cliff-top storm deposits have been identified close to the D3100 site [153, ¶29], suggesting that waves do not tend to exceed the height of the cliffs.

Tsunami

312 The risk of a tsunami hitting the UK has been studied in detail by the UK Government (Defra [260]). Seven possible tsunami sources have been identified [260, Fig.2.1]; of these, the greatest risk to northern Scotland is posed by a landslide-triggered event. Around 7,200 years ago a major tsunami is believed to have hit northern and eastern Scotland. This tsunami was triggered by a submarine landslide, the Storegga Slide, in which large volumes of glacial-derived Pliocene-Pleistocene sediment originating from Scandinavia flowed down the continental margin west of Norway. It is believed that the Storegga Slide is only the most recent of a series of large submarine landslides that have occurred to the west of mid-Norway over the last 500,000 years [260, §2.2.2.2]. The tsunami that the Storegga Slide generated is believed to have exhibited waves up to ca. 20 m high in Shetland but only 3 to 4 m

high in northeast Scotland [260, §2.2.2.2]. The current probability of a landslide-derived tsunami in the seas north of Scotland is considered to be very low [260, §2.2.2.4]. If an event similar to the Storegga Slide was to occur in the future, it is unlikely that wave heights would exceed the cliff height at the D3100 site, even with moderate sea level rise in the interim.

313 If a large hypothetical tsunami exceeded the cliff height (possibly as a result of sea level rise in thousands of years' time), it is likely it would cause only superficial erosive damage to the top of the cap and not significantly impact the wastes inside the vaults. Because of the topography, it is considered that the sea water from the wave would quickly drain away. As such, tsunamis are not considered to threaten the performance of D3100.

Changes in relative sea-level

314 Relative sea-level rise is the result of two processes – changes in global sea-level (eustatic sea-level) and changes in the height of the land (isostatic changes). The net result of these processes is the relative sea-level change that would be witnessed by an observer on the foreshore.

315 Changes in eustatic sea level are driven by changes in climate. DSRL undertook a review of potential climate change effects at Dounreay in 2007 to support siting analysis [153]. The continuing validity of the review and its conclusions are checked periodically against the most recent published literature. The latest review was in 2019 [261]. The overall conclusions are that global warming is likely in the next few hundreds to thousands of years, resulting in partial melting of the polar ice sheets and thermal expansion of the ocean waters. Both of these processes will contribute to a rise in global (eustatic) sea levels. Thereafter, sea level and temperatures are likely to remain high for tens to hundreds of thousands of years, before global cooling commences, eventually leading to the next glacial cycle.

316 There are significant uncertainties in the magnitude and timing of sea-level change in relation to this broad picture because of uncertainties in the pattern of greenhouse gas emissions and uncertainties in the response of the atmosphere-hydrosphere-cryosphere to these emissions. The DSRL review of climate change [153] concludes that rises of 7 m might occur within several thousand years if the Greenland ice-sheet melts. A further rise of 5 m could occur if there was complete collapse of the West Antarctic Ice Sheet. This would require that global average warming was sustained for millennia in excess of 1.9 to 4.6^{o}C relative to pre-industrial values.

317 With regard to isostatic changes, Scotland has, for the past 13,000 years or so, been responding to the removal of the ice at the end of the last glaciation. The response pattern is complex along the northern coast of Scotland. However, BGS studies [262] of accretion rates of saltmarsh deposits indicate that stable environmental conditions have existed over a considerable period at the mouth of the River Naver at Bettyhill, about 28 km to the west of Dounreay. On the basis of this analysis, the BGS has argued that there is no evidence of current crustal uplift or subsidence at the Strath Naver site and that isostatic uplift may have ceased at Dounreay [262]. The BGS's conclusions are consistent with academic work (e.g. [263; 264]), which has estimated an isostatic uplift of between 0 mm y^{-1} and 0.5 mm y^{-1} along the northern coast of Scotland.

318 The combination of these data on eustatic changes and isostatic movements suggest that, disregarding extreme scenarios of climate change, a best *upper* estimate of around +12 m AOD can be made for the relative sea-level rise at Dounreay over several thousands of years [153; 261]. The location of D3100 at the 24-29 m AOD contour significantly reduces the risk that the top of the facilities will be inundated by sea-level rise, even when combined with a future storm surge or tsunami (see above). For example, assuming a similar increase in peak flood elevation for future storm surges to that at present, a +12 m AOD sea level rise combined with a large storm surge (ca. 8 m high) would not reach the top of the facilities.

319 Climate modelling of the northern hemisphere has suggested that it will take at least 50,000 years to recover from the impacts of human activities (e.g. [265]). However, other modelling results indicate that this recovery period could be more than ten times longer (ca. 500,000 years, see Section 6.3.4) if high greenhouse gas emissions scenarios persist [153, ¶45]. With such large uncertainties in long-term climate change modelling, it could be assumed that cooling in the northern hemisphere will not start to take place until after 50,000 years and possibly not until much later. Therefore, relative sea level at Dounreay could remain at +12 m AOD for an extended period.

320 As with warming, the subsequent cooling period is highly uncertain, and may occur from some stage after 50,000 years, until the glacial maximum is established [153, ¶46]. During this cooling period, there will be a substantial fall in sea level, as water becomes incorporated into continental ice sheets. Relative sea level at Dounreay is assumed to fall gradually from a peak of +12 m AOD towards its present level and then further to a minimum level coinciding with the next glacial maximum. At this stage, global sea levels may have fallen to as low as 120 m below the present-day sea level, although relative sea-level at Dounreay will be affected by depression of the land surface by ice loading.

6.3.2 Coastal erosion

321 Although marine inundation is the most obvious consequence to be expected from sea-level rise, coastal erosion leading to significant coastal retreat is also a potential threat to current land use. Realistic estimates of long-term erosion rates for the cliffs at Dounreay are highly uncertain. However, estimates of short-term coastal erosion rates at Dounreay have been derived for projects concerned with the Shaft and the LLW Pits (e.g. [266]). There is an inherent difficulty in extrapolating short-term (years) and small-scale (mm) processes and measurements to predict long-term (thousands of years) and large-scale (landform) changes. A review of evidence for erosion rates at Dounreay is provided in [153].

322 The Quaternary superficials on top of the Devonian bedrock are eroded more uniformly and more rapidly than the bedrock, owing to their unconsolidated nature. However, at the present time, the rockhead level seaward of D3100 is such that erosion of the flagstones is governing the recessive erosion rate of the Dounreay cliffs [266]. The intrinsic average recession rate of the more resistant flagstone layers, consisting of massive, cemented, low-porosity beds, is low, estimated at less than 0.05 mm y^{-1} by [259]. However, the main control on the long-term recessive erosion rate of the cliffs at Dounreay is the rate of slot deepening in the more porous,

less competent flagstone interbeds [259]. These are fissile, thinly-bedded sandstones, siltstones, shales and impure limestones, the erosion of which proceeds chiefly by the erosion of finer-grained layers. This mechanism causes the development of horizontal slots, both by groundwater seepage and wave action, that deepen until slabs of the remaining, more competent, rock become loose or fall down by cantilever failure [259]. It has been suggested that this process could be occurring at a relatively greater rate of between 10 and 50 mm y^{-1} [259].

323 In addition to direct erosion of the cliffs, erosion can penetrate the coastline along less erosion-resistant fault-lines marked by geos. A rate for post-glacial penetration of geos close to the Dounreay site was derived by [259] on the basis on archaeological evidence. A broch at Green Tullochs is partially penetrated by a narrow geo, Geo Croiche. Taking an archaeologically acceptable date for the broch of around 2,000 years before present (BP), an average rate of lengthening of the geo of 2 to 9 mm y^{-1} can be estimated. However, there are a number of uncertainties associated with applying estimations of geo lengthening to long-term cliff erosion: a geo may not be facing the predominant direction of incoming waves; a geo is a coastal expression of a fault zone, and the material present in a geo may not be representative of the main rock mass in the cliffs; and groundwater discharge from a geo will be higher than from the main body of the cliff, owing to faulting, thus accelerating erosion and geo lengthening.

324 Information on erosion rates can also be derived from studies elsewhere, although there will be significant uncertainties in the application of such rates because of differences in lithology, coastal morphology and the frequency and magnitude of the storms that are the principal causes of erosion. A worldwide review of lateral sea-cliff erosion rates was presented by [267]. The rates for granitic rocks and limestones are given as about 1 mm y^{-1} and 1 to 10 mm y^{-1}, respectively. Assuming a flagstone lithology has an erosion resistance between that for granite and that for limestone, a cautious upper average rate for flagstones is considered to be 10 mm y^{-1}.

325 The maximum rate of geo extension measured by [259] and the corresponding maximum general rate of hard rock erosion (10 mm y^{-1}) have been taken by the D3100 project to represent a reasonable upper estimate for general coastal erosion in the Dounreay area [153]; the actual long-term erosion rate is likely to be less than this. Given the uncertainties over the duration of elevated sea levels and long-term erosion rates, no location on NDA-owned land at Dounreay could be chosen to rule out completely the possibility of erosion at some time in the far future. Such a scenario has been considered in the D3100 PA and is discussed in Section 7.

326 For confidence-building purposes, DSRL has agreed with SEPA to establish a robust baseline against which future erosion might be measured. On behalf of DSRL, the BGS compiled available cartographic, aerial photo and remote sensing datasets into a geographical information system (GIS) in order to define such a baseline [268]. In general, these data show that the coastline has been stable within the accuracy of the survey and interpretative techniques applied. More recently, BGS has used digital photogrammetry, detailed examination of large-scale georectified topographic mapping, and differential global positioning satellite surveying techniques to quantify coastal changes in the Dounreay area [269]. Taken together, these techniques indicate that much of the coastline has been subject to only gradual change and that

significant alteration of the cliff-line position has only occurred where most of the cliff profile is developed of superficial deposits. There is no unambiguous evidence of noticeable recession of the natural cliff-line during the last hundred years or more. DSRL will continue to monitor any changes, as described in Section 10.2.2.

6.3.3 Seismic activity

327 A seismic event is caused by 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. Seismic events may result in changes in the physical properties of rocks due to stress changes and induced hydrological changes. Seismic events are most common in tectonically active or volcanically active regions at crustal plate margins. The seismic waves that are generated by a tectonic or volcanic disturbance of the ocean floor may result in a tsunami (Section 6.3.1).

328 Northern Scotland lies within the continental "passive margin" area of the Eurasian plate, which underlies north-western Europe and beyond, and has been seismically stable for about 200 million years. Small crustal movements occurred in the region as a result of stress changes during the last glaciation/de-glaciation (ca. 10,000 years ago). At present, D3100 is unlikely to be affected by seismic events under the current stable north-south stress regime in Northern Scotland [270]. Peak seismic-induced ground accelerations over different return periods have been estimated by the BGS [271]. In the region surrounding the D3100 site, predicted ground accelerations are lower than those in much of the rest of the UK.

329 Large earthquakes as a consequence of glaciation and a new cycle of isostatic rebound are unlikely to occur in the next 100,000 years (e.g. [153, ¶38]) (see Section 6.3.4).

6.3.4 Glaciation

330 As global climate becomes significantly cooler in the very far future, the climate in the region of the Dounreay site will be modified, becoming similar to the typical present-day regimes at more northerly latitudes, such as Iceland, northern Scandinavia and northern Russia. Regional centres of glacial development are expected to form in the highland regions of Scotland and in Scandinavia, and these would extend outwards as the cooling continued.

331 In the first instance, periglacial conditions would persist in Northern Scotland during the colder periods and permafrost might also develop at Dounreay. Permafrost would affect the hydrogeology in the vicinity of D3100, and could contribute to the degradation of facility engineering.

332 Research into glacial initiation has suggested that anthropogenic climate change has greatly altered the timing at which future glaciation of the northern hemisphere is likely to occur. Modelling has suggested that at pre-industrial atmospheric CO_2 levels (ca. < 280 ppm), glaciation would likely start to occur in around 50,000 to 60,000 years (e.g. [272; 273]). At current atmospheric CO_2 concentrations, it has been suggested that glacial conditions could not initiate [274]. However, through weathering processes, atmospheric CO_2 concentrations are likely to slowly decline

over tens of thousands of years, eventually dropping to a level that will allow for initiation of glacial conditions. The next glaciation is likely to be delayed, at minimum, by around 50,000 years. Modelling results suggest that the next glaciation is likely to occur in ca. 100,000 to 500,000 years, with the timing dependent on the severity of anthropogenic CO_2 emissions over the next few hundred to thousand years [272; 273].

6.4 Future Site Characterisation

GRA 6.4.7	Establish a proportionate approach to site investigation that uses some or all of the results from site characterisation, modelling studies, design and construction to guide investigations. The site investigation should be presented as part of a structured programme that provides the requisite information for the environmental safety case.
GRA 6.4.13	Before carrying out any intrusive geological investigations, assess the extent to which these might disturb the site and any implications this might have for the environmental safety case.
GRA 6.4.20(a)	Show that the geological conditions in each section of the disposal facility, as disturbed by construction, are suitable for the types and quantities of waste that it is proposed to dispose of in that section.
GRA 6.4.35	Carry out appropriate investigation and monitoring during the construction stage and period of authorisation to establish: the characteristics of the site; the behaviour of the disposal system; and the extent of disturbance caused by intrusive site investigation procedures and by construction, operation and closure of the facility.

333 The site characterisation work to date and its interpretation is summarised in Site Characteristics Summary 2020 [50]. DSRL considers that the site characteristics of D3100 are sufficiently well understood to support this ESC. The last iteration of the D3100 site characterisation plan, SCP 2011 [198], specified the characterisation activities to be conducted during construction of the Phase 1 D3100 vaults. As such, SCP 2011 largely reflected the Contractor's SCP for design-and-build, and the plan to refine the site characteristics for the ESC in SCP 2011 was not a consequence of there being any significant uncertainties in the geological, hydrogeological or geotechnical understanding of the site that impact the ESC. Rather, it simply reflected the opportunity to use new site information as it became available during construction.

334 Site characterisation has essentially ceased, at least for now, on the completion of construction of the Phase 1 vaults, although monitoring will continue throughout the period of authorisation. These monitoring activities are covered in Section 10, and the monitoring data may inform refinements in understanding of the characteristics of the D3100 site area. Nevertheless, similar opportunities to those set out in SCP 2011 to develop site understanding may occur during the construction of future phases of vaults. Site characterisation activities that might be considered during future vault construction include [198]:

- Geology: although the stratigraphy and geological structure of the D3100 study area are characterised to the extent needed by the ESC, the exact spatial dispositions of some of the faults are not known in detail. During further excavations, it is likely that new geological information could be acquired, and this could be used to verify and, where necessary, refine understanding of the site geology.

- Hydrogeology: development of the local-scale hydrogeological model to consider ongoing needs of construction/operation activities.
- Geomechanical properties: during Phase 2 and Phase 3 vault construction, additional measurements of rock quality, including load-bearing tests, and further assessments of slope stability will likely be necessary, and the Contractor will define any additional site characterisation required.

335 As the D3100 project proceeds, characterisation boreholes that are not to be maintained for monitoring will need to be decommissioned. The decommissioning methodology has been discussed with SEPA and involves backfilling and sealing designed to ensure that the boreholes are structurally stable, do not act as preferential pathways for groundwater flow, and do not allow flow of water between the different groundwater systems and to the surface.

336 Minor site characterisation activities are also conducted occasionally as the opportunity and need are identified by ongoing interpretation work. For example, a study of the mineral precipitates around the groundwater pumps and a re-evaluation of the geochemical modelling work undertaken prior to construction have recently been undertaken to support interpretation of the water quality monitoring.

FP.7	Evaluate site characterisation opportunities during future phases of vault construction.

7 ASSESSMENT OF SAFETY

337 This section addresses the detailed requirements in the GRA related to the safety assessments of D3100. This is done mainly through quantitative modelling, such as the D3100 PA [48]. However, assessments are only one key input to the consideration of safety – additional considerations are provided in Section 9.

338 Several assessments with different objectives or endpoints are needed to meet the requirements of the GRA [19], including assessment of:

- Radiological dose/risk to the public during operations and after closure, including risks from gas releases and inadvertent human intrusion, addressing Requirements R5, R6 and R7.
- Radiological impacts on the environment and on non-human species, addressing Requirement R9.
- Non-radiological risks to the public and the environment, addressing Requirement R10.
- Other issues to support optimisation, design and waste acceptance decisions, such as criticality and collective doses.

339 The degree of quantitative modelling involved in each of these assessments is not fixed, and the effort involved needs to be proportionate to the hazards being considered. The approach taken by the D3100 project, consistent with other radioactive waste disposal programmes, is to focus most effort on development of a quantitative assessment capability for radiological dose and risk to the public. An internationally recognised formal methodology has been followed to develop the radiological dose/risk, or safety, assessment, and this is described first below. The radiological safety assessment models, data and results have then been adapted as necessary to support development of the other assessments that are needed, thereby giving these assessments the same founding and scientific basis. The additional assessments are described after the radiological safety assessment towards the end of this section. Finally, consideration is given to further development of the assessment capability to support future work.

7.1 Dounreay D3100 Project Radiological Safety Assessment

340 Between 2000 and 2002, UKAEA undertook a quantitative post-closure radiological safety assessment, or performance assessment (PA), referred to as the Run 1 PA, as part of the Stage 1 LLW BPEO study. Two independent sets of calculations for the Run 1 PA were developed: one each by two experienced PA contractors, Galson Sciences Limited (GSL) [157] and Enviros QuantiSci (EQ) [158]. The development of two sets of PA calculations was undertaken to build confidence in the PA results and provide a means of evaluating the differences and similarities between different PA methodologies and tools [275].

341 Since Run 1, there have been changes to the location, layout and engineering design of D3100, driven by optimisation analyses and an increased understanding of the geology and hydrogeology of the D3100 study area resulting from site characterisation activities. A second iteration, Run 2, of the D3100 project PA was

conducted in 2007/2008 [276], building on the understanding gained in Run 1 and focusing model development on providing support for ongoing project activities, such as design and optimisation. The Run 2 PA was used to support the ESC 2008 issue that, in turn, supported the planning application for D3100. In 2008-09, SEPA commissioned Brenk Systemplanung GmbH to review the Run 2 PA [277]. A further iteration of the D3100 project PA (the Run 3 PA [278]) was then developed to address the Brenk and SEPA comments and support ESC 2010 Issue 1. To accompany completion of Phase 1 construction of disposal vaults, DSRL issued an updated ESC in 2015 [29], this was supported by the Run 4 PA [279]. Key changes in the Run 4 PA were model alternations undertaken to better reflect the constructed design of D3100. This section discusses results from the most recent iteration of the DSRL D3100 PA, the Run 5 PA [48], that has been undertaken to support the transition to a SoF approach for waste acceptance at D3100 (see Section 8) and the results of which are presented in this update of the ESC.

342 For all iterations of the D3100 project PA, a formalised and systematic assessment methodology has been adopted. Application of such a methodology is important to build confidence in the PA. A systematic assessment methodology that is clear and transparent helps to ensure the use of appropriate and auditable information, that arguments are sound and decisions justified, that the sensitivity of results is considered, and that uncertainties are identified and assessed appropriately.

343 In the context of near-surface radioactive waste disposal facilities, such as D3100 at Dounreay, a PA methodology was developed as part of the ISAM Coordinated Research Project of the IAEA [64]. Hereafter, we refer to this as the "ISAM methodology", and the methodology adopted for the D3100 project PA is consistent with the ISAM methodology. While the ISAM methodology is now somewhat dated and has been developed further in international work, such as that by the IAEA [24] and the NEA [280], its structure is still essentially valid and it is used here to structure the presentation of the formal elements of the D3100 PA. The main stages in the ISAM methodology are illustrated in Figure 7.1. The documentation for the Run 5 PA is structured to reflect these stages, as shown in Figure 7.1. However, the main evaluation of the PA results, as indicated in the flow diagram at the bottom of Figure 7.1, is undertaken in this ESC in the context of implications of the results for the development of D3100.

344 The following sections describe the Run 5 PA development and results, and are ordered to reflect the methodological approach taken to developing the PA, as illustrated in Figure 7.1.

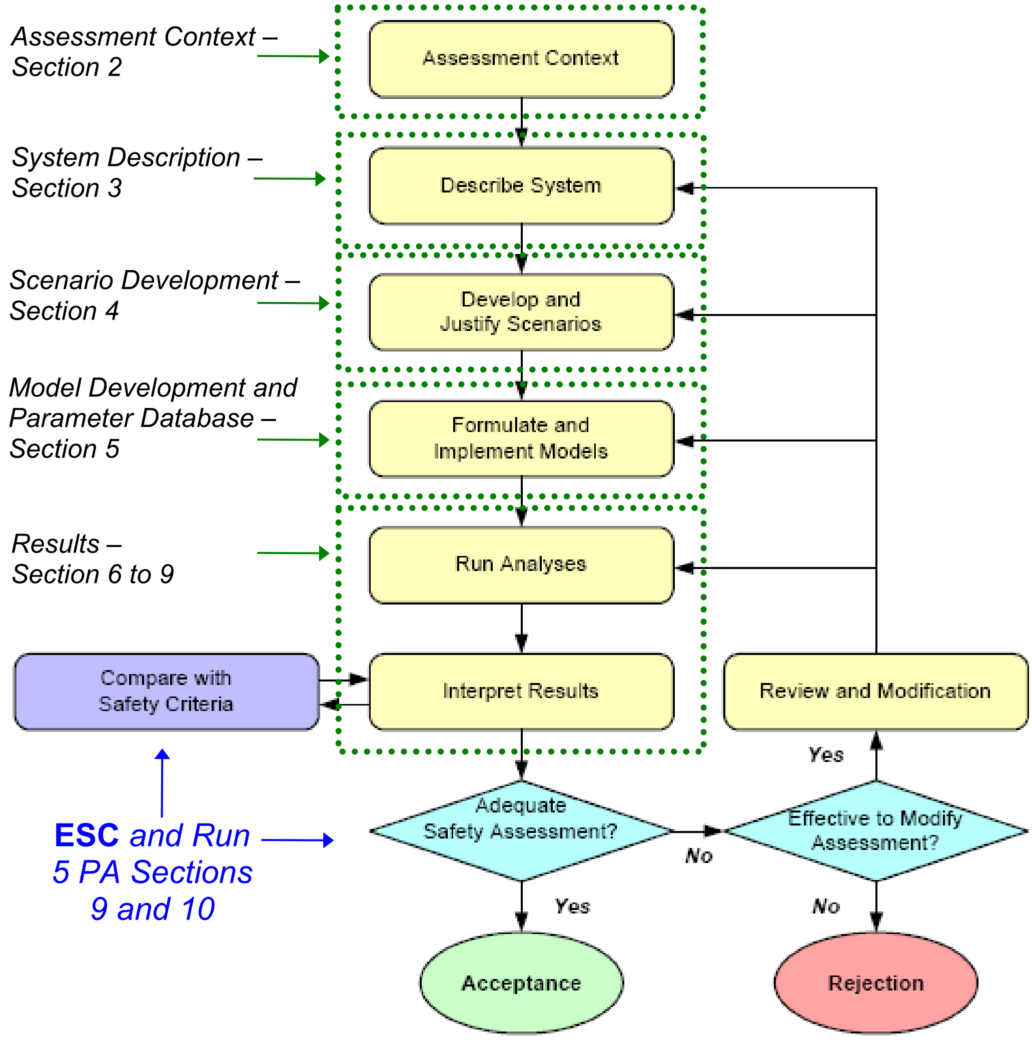

Figure 7.1: The ISAM PA methodology [64]. Green dotted boxes and italic text on the left show the sections in the Run 5 PA report [48] corresponding to each stage of the methodology. The evaluation of the PA and its implications are considered primarily in this ESC, as well as there being a discussion in Sections 9 and 10 of the PA report, as indicated by the blue text.

7.2 Run 5 PA Assessment Context

GRA 7.2.8(a)	The environmental safety case should include quantitative environmental safety assessments for both the period of authorisation and afterwards. These assessments will need to extend into the future until the radiological risks have peaked or until the uncertainties have become so great that quantitative assessments cease to be meaningful.
GRA 7.3.5	Provide one or more quantitative assessments aimed at calculating risk, which can then be compared to the risk guidance level, as a key part of the environmental safety case for times after the period of authorisation.

GRA 7.3.21	Provide details of the models and methodologies used in the environmental safety assessment including any assumptions, as well as the results.
GRA 7.2.5	Everything significant that is claimed or assumed in the environmental safety case should be supported by evidence that is adequate in content and is of appropriate type or types, detail and robustness.

7.2.1 Run 5 PA objectives and scope

345 The primary objective of the Run 5 PA is to consider the post-closure radiological performance of D3100 to support this ESC and serve as a basis for the EASR 18 Permit. The Run 3 PA, the last iteration formally reviewed by SEPA, had similar primary objectives. However, there have been a number of developments since the Run 3 PA that have been addressed in Runs 4 and 5.

346 During Phase 1 development, there were several key changes in the D3100 design:

- Pairing of each phase of LLW and Demolition LLW vaults together, rather than separation of a LLW vaults area and a Demolition LLW vaults area.
- Location and separation of each phase of vaults to facilitate security arrangements, to allow disposal operations to continue while future construction takes place, and to allow excavation of future vaults by blasting. This has resulted in the vaults covering a slightly larger footprint.
- Retaining a wall of rock between each adjoining LLW and Demolition LLW vaults to allow separate closure of each vault.
- Adjustment of the dimensions (width versus length) of the Demolition LLW vaults to fit with the length of the adjacent LLW vault. The first phase of vaults has been constructed to accommodate the lowest anticipated volume of waste (i.e. the minimum vault capacity that will definitely be needed); the size of the subsequent phases of vaults will be reviewed as necessary as estimates of waste volumes are refined during decommissioning.
- Increase in width of the LLW vaults to accommodate a row of eight HHISO-type containers placed end-to-end, rather than seven.
- Increase in the thickness of the concrete walls of the Demolition LLW vaults from 500 mm to 1,100 mm.
- Installation of an "enhanced geosphere" barrier – a layer of excavated material placed on the existing ground surface between the vaults and the coast to ensure that the groundwater table remains below the new ground surface.

347 The design changes outlined above were incorporated into the D3100 PA model as part of Run 4:

- The location and pairing of vaults were modified to reflect the current design.
- The "enhanced geosphere" between the vaults and the coast was incorporated into the model.
- Parameterisation changes were undertaken to reflect the current design (e.g. Demolition LLW vault wall thickness, adjustment of vault dimensions).

- Changes to the scenarios considered as part of the inadvertent human intrusion model of the D3100 PA to better reflect the characteristics of the constructed vaults.

348 This iteration of the D3100 ESC has been produced to support an application to SEPA to vary the Permit to apply a risk-based approach to setting radioactivity limits for waste disposals. As such, Run 5 development has focused on enhancing key aspects of the model to remove undue conservatism. The main changes resulting from this are:

- Updates to the gas conceptual model, its mathematical basis and associated parameters. This includes reconsideration of the ^{14}C gas pathway, which has been updated following the approach used in gas PA modelling at the LLWR.
- Enhancement of the D3100 groundwater and gas models to allow consideration of both conditional and calculated risk.
- An update to the estimated inventory. The Run 5 PA considers the 2020 Case B and Demolition best estimate inventories reported in Section 4.3 and [47].

349 The Run 5 PA does not consider:

- Operational safety issues. The only pathway for possible exposure of the public during operation of D3100 is skyshine from waste packages emplaced in the vaults. Potential doses from skyshine have been determined in a separate assessment to the Run 5 PA (see Section 7.8). The risks associated with accidental releases and doses to workers are beyond the scope of this ESC and the Run 5 PA.
- Impacts other than those associated with the effect of radioactivity on human health. Radiological impacts on other flora and fauna have been considered separately (see Section 7.9).
- Non-radiological hazards associated with the Dounreay LLW (see Section 7.10). However, the Run 5 PA models and end-points have been developed such that it would be straightforward to use them for non-radiological hazard assessments, should such assessments be identified as necessary.
- Cumulative radiological impacts from any other part of, or facility at, the Dounreay licensed site. Requirement R5 of the GRA [19] considers the potential cumulative impact of radioactivity from all sources. However, cumulative impacts can be conservatively calculated simply by summing the results of the Run 5 PA with the results of PAs for other sources of radioactivity at Dounreay (e.g. the Shaft) assuming that the same sections of the biosphere are being considered in each PA (see Section 7.5.3).
- Collective dose. The consideration of collective radiological impacts is discussed in the GRA [19, ¶6.3.68 and 6.3.69], but only in the context of its use as a potential discriminator between different waste management

options. Such a use has not been identified to date in the D3100 project (see Section 7.12).

- Deliberate human intrusion, which is excluded by the GRA [19, ¶6.3.41].

350 The Run 5 PA calculations assume that:

- Future generations do not act to maintain the integrity of the disposal system after closure (GRA Principle 4).

7.2.2 Performance measures

351 The GRA [19] defines three numerical performance measures to satisfy regulatory requirements for radiological protection of humans:

- **Requirement R5: Dose constraints during the period of authorisation.** During the period of authorisation, the effective dose from the facility to a representative member of the critical group should not exceed a source-related dose constraint and a site-related dose constraint. The following are the maximum doses to individuals which may result from a defined source, for use at the planning stage in radiation protection: 0.3 mSv y^{-1} from any source from which radioactive discharges are made[25]; or 0.5 mSv y^{-1} from the discharges from any single site.
- **Requirement R6: Risk guidance level after the period of authorisation.** 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} y^{-1} (i.e. one in a million per year).
- **Requirement R7: Human intrusion after the period of authorisation.** The developer/operator of a near-surface disposal facility should assess the potential consequences of human intrusion into the facility after the period of authorisation on the basis that it is likely to occur. The developer/operator should, however, consider and implement any practical measures that might reduce the chance of its happening. The assessed effective dose to any person during and after the assumed intrusion should not exceed a dose guidance level in the range of around 3 mSv y^{-1} to around 20 mSv y^{-1}. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of years (prolonged exposures), while values towards the upper end of the range are applicable to assessed exposures that are only short term (transitory exposures).

352 Several terms in these requirements require definition. The period of authorisation is the time while disposals are taking place and any period afterwards while the site is under active institutional control and subject to authorisation, initially under RSA 93 and now EASR 18, by SEPA. For Requirement R5, the source-related constraint is applied to D3100 as a single source of radioactive releases, and the site-related

[25] The HPA has recommended a slightly lower dose constraint for the operational phase of a new disposal facility of 0.15 mSv per year [68].

constraint is applied to D3100 and any releases from the adjoining Dounreay nuclear licensed site. The D3100 site and the decommissioned Dounreay nuclear licensed site will be monitored together during the institutional control period, and the period of authorisation will, therefore, likely be the same for both. However, the two sources are subject to separate Permits under EASR 18. The dose constraint in Requirement R5 is specified in terms of the exposure of a representative member of the critical group. An exposed group is any group of people within which the exposure to radiation is reasonably homogeneous. The critical group is the exposed group (from a selection of potential critical groups) receiving the highest dose from the facilities. For Requirement R6, where the exposure is not certain to occur, a set of potentially exposed groups (PEGs) is defined and assessed in order to identify the group and, therefore, the representative person at greatest risk at a given time. For Requirement R7, radiation doses to individuals, rather than groups, exposed as a result of inadvertent human intrusion events are considered, representative of those undertaking the intrusion and those who might occupy the site afterwards.

353 The term “representative person” (RP) has been introduced by the ICRP [281] to replace the terminology of critical group and PEG, and has been adopted in recent UK regulatory guidance, such as the Guidance on Requirements for Release from Radioactive Substances Regulation [46]. The RP is defined as an *“individual receiving a dose that is representative of the more highly exposed individuals in the population”* and the GRR states that the RP is *“equivalent of, and replaces”* the *“average member of the critical group”* and *“potentially exposed group”*. DSRL has been informed by SEPA that the term RP will be used in place of critical group and PEG in the update of the GRA. As such, RP, rather than critical group and PEG, is used in the Run 5 PA and herein in regards to Requirements R5 to R7 of the GRA.

354 The primary end-points for the Run 5 PA are radiological effective dose[26] to the RP during the period of authorisation, radiological risk to potential RPs after the period of authorisation, and radiological effective dose to an intruder during inadvertent human intrusion and subsequently to any exposed potential RPs.

355 Radiological risk to an RP considered under Requirement R6 is the product of the probability that the dose will result in a serious health effect and probability that a given dose will be received, summed over all situations that could give rise to exposure to the RP. For the former probability, the GRA states that a dose-risk factor of 0.06 Sv^{-1} should be used for situations in which only stochastic effects of radiation exposure need to be considered (i.e. when the estimated annual effective dose is less than 100 mSv and the estimated equivalent dose to each tissue is below the relevant threshold for deterministic effects). This corresponds to recommendations set out in the advice of the HPA on the disposal of solid radioactive waste [68]. For the latter probability, two approaches are used in the Run 5 PA:

[26] “Radiological” is an adjective to explicitly identify that the dose relates to radioactivity. “Effective dose” (as used in the regulatory guidance) is considered here as equivalent to the ICRP quantity that takes into account the type of radiation and the nature of each organ or tissue being irradiated for each radionuclide and is calculated using committed effective dose coefficients for intake of radionuclides by ingestion and / or inhalation and effective dose rates for unit external exposure to radiation.

- Calculation of conditional risk: It is assumed that the probability that the calculated dose will be received by the RP is one.
- Calculation of actual risk: Further consideration is given to the probability that a given dose will be received. This is undertaken for a range of possible activities through calculation of an expectation value for the probability that the area needed for each activity will be located in an area potentially contaminated by radionuclide releases from D3100. Further details on this calculation are presented in Section 7.5.3.

356 Two additional performance measures considered in the Run 5 PA are concentrations of radionuclides in environmental media (soils, rocks, waters) over time, and fluxes of radioactivity into different areas of the environment. Concentrations are needed to evaluate radiological impacts on the wider environment, as needed by Requirement R9 in the GRA [19], and are a useful safety indicator when considering changes in the levels of radioactivity in the accessible environment. Fluxes are a useful intermediate performance measure with which to evaluate performance of facility engineering as part of optimisation analyses, and can also be used in comparison with natural fluxes of radionuclides in the environment.

7.2.3 Treatment of uncertainty and specification of calculation cases

GRA 6.3.21	In setting up a risk assessment, aim for data and assumptions that represent realistic or best estimates of the system behaviour. However, where the data do not support this approach or where the assessment can usefully be simplified, conservative data and assumptions to be conservative can be chosen as long as the requirements are still shown to be met.
GRA 6.3.26(b)	Unquantifiable uncertainties (where, for example, it is not possible to acquire relevant data, or if acquiring enough data to evaluate the uncertainty statistically could only be done at disproportionate cost) need to be taken into account in developing the safety case, but should be kept apart from the quantifiable uncertainties and given separate consideration. Taking into account unquantifiable uncertainties will inevitably involve judgement, first identifying significant unquantifiable uncertainties and then considering ‘balance of likelihood’.
GRA 6.3.28	For highly uncertain future events, consider whether it is appropriate to undertake numerical risk assessments for comparison with the risk guidance level (e.g. “what-if” scenarios and human actions that affect the disposal system).
GRA 7.3.12	Account for both readily quantifiable and unquantifiable uncertainty types in the environmental safety case.
GRA 7.3.17	If unquantifiable uncertainties are important to the ESC, they may be treated by a series of risk assessments, in each case making deterministic assumptions and exploring the effects of varying these assumptions.

GRA 7.3.18	In some circumstances, where few or no relevant data can be gathered, a 'stylised' approach to assessment may be adopted, in which arbitrary assumptions are made that are plausible and internally consistent but tend to err on the side of conservatism. Use of a stylised approach should not distort the modelling of the rest of the system such that important properties of other parts of the system are obscured in the overall model.
GRA 7.3.30	Where expert judgement that is not held in common is used to complement or interpret evidence or to compensate for data gaps, to an extent proportionate to the significance of the judgements to the environmental safety case: - explain the choice of experts and method of elicitation; - document explicitly expert judgements that have been made and the reasons given by experts to support their judgements; - take and document reasonable steps to identify and eliminate or minimise any biases resulting from the use of expert judgement and/or the elicitation methods adopted.

357 Any PA model is, by its nature, a simplification of reality. This is particularly true for the PA of a radioactive waste disposal system given the long timescales and complexities that need to be taken into account. Therefore, PA calculations are only indicative and are constructed to illustrate potential consequences as an aid to decision-making. Uncertainties are dealt with by making multiple sets of calculations to evaluate the performance of the disposal system under different sets of conditions. The D3100 project PA adopts a standard approach to considering uncertainty in a PA for radioactive waste disposal (e.g. see [280]), by partitioning uncertainty into three categories:

- Uncertainty in the future evolution of the disposal system, referred to as **scenario uncertainty**.
- Uncertainty in the models used to represent this evolution, introduced through the inevitable assumptions and, in some cases, simplifications made in developing the models, referred to as **model uncertainty**. This can be sub-divided into conceptual model uncertainty and mathematical and numerical model uncertainty.
- Uncertainty in the parameter values used in the modelling programme to evaluate the potential consequences of scenarios, referred to as **parameter uncertainty**.

358 For the D3100 project PA, where possible, uncertainties are defined in terms of parameter value ranges. For example, there is considerable uncertainty over the exact duration and magnitude of future climate changes. These uncertainties could be treated as scenario uncertainty. However, ranges can be defined for many climate-related parameters, such as the rate of cliff erosion, and these ranges are treated in the PA as parameter uncertainty until the range reaches a limit that causes a fundamentally different future evolution (scenario) for the system. For example, when the cliff erosion rate, in combination with the duration of eroding conditions, exceeds the limit when the facilities would be eroded, such an event is treated as scenario uncertainty.

359 The D3100 project PA considers scenario and model uncertainties by defining alternative deterministic calculation cases. For the Run 3 PA, a complete set of scenario descriptions and a list of alternative modelling assumptions were compiled in [278] to aid transparency in this treatment. The Run 3 treatment has been reviewed and re-evaluated where necessary in Run 4 [279] and Run 5 [48]. For each deterministic calculation, a best estimate of the parameter values is used. Realistic modelling assumptions and parameter values have been adopted where possible [19, ¶6.3.21]. However, cautious or conservative assumptions and parameter values have been used where uncertainties prevent a more realistic approach or where model simplifications are possible without significantly affecting the assessment outcome.

360 The deterministic calculations illustrate the potential consequences of each scenario / alternative model. In accordance with the GRA [19, Fig.6.2, ¶6.3.26], unquantifiable uncertainties or uncertainties that are difficult to quantify reliably relating to events that could have a significant impact on the disposal system have generally been defined as separate scenarios. For some of these scenarios (e.g. ground rupture and coastal erosion), the deterministic calculations yield conditional risks that are then compared to the regulatory risk guidance level taking into account, at a qualitative level, the likelihood associated with each calculation. For scenarios concerned with inadvertent human intrusion and disruptive human actions, the doses calculated are compared to the deterministic dose guidance level, which is defined specifically in the GRA to avoid the need for speculative predictions of future human activity.

361 Mathematical and numerical model uncertainties are, in general, considered to be small compared to the conceptual model uncertainties evaluated in the Run 3 to 5 PAs. Mathematical and numerical model uncertainties have largely been considered for the D3100 project in the development of the PA model, rather than in specifying alternative calculations. For example, discretisation of the flow paths was considered in setting up the PA model to ensure that the results from the PA are fit for purpose [278, App.2].

362 Within each Run 5 scenario, parameter uncertainties are evaluated using deterministic analysis. Key parameter uncertainties have been identified and retained or excluded on the basis of previous D3100 project PA results and experience of other PAs for similar facilities. Where uncertainty ranges and distributions can be quantified for parameters, worst case deterministic alternative calculations have been used in Run 5 to evaluate the consequences of parameter uncertainty and the sensitivity of results to each parameter. Some probabilistic simulations sampling the uncertainty ranges were also undertaken in Run 3 [278] and Run 4 [279]. In cases where uncertainty ranges and distributions for parameters are not readily quantifiable, deterministic bounding or stylised calculation cases have been defined to evaluate the potential consequences of the parameter uncertainty.

363 As identified in the GRA, deterministic calculations can also be used to illustrate results associated with “what-if” conditions that are highly uncertain or to inform analysis of the disposal system. A series of “what-if” calculations were undertaken using the Run 2 PA models, but outside the reporting of the Run 2 PA, in order to analyse the performance of each engineered barrier in the disposal system in

isolation (i.e. all the other barriers were assumed to have failed, a condition that has not been identified in the D3100 project PA scenario development analysis) [282]. For Run 5, a subset of scenario and parameter uncertainties considered are classed as "what-if" calculations. These calculations consider highly speculative and unlikely future outcomes for D3100 facility and/or associated systems. As such, they do not reflect uncertainty in the characteristics of the disposal system.

7.3 Run 5 PA System Description

364 The system description for the Run 5 PA [48, Ch.3] provides information about the disposal system upon which the PA was undertaken. It is divided according to the main components or barriers of the disposal system [64]:

- Near-field. The waste, the disposal area, the engineered barriers of the disposal facilities, and the disturbed zone of the natural barriers that surround the disposal facilities. The engineered cap and enhanced geosphere are included in this component.
- Geosphere. The rock and any remaining Quaternary cover material following construction of D3100 that lie between the near-field and the biosphere.
- Biosphere. The physical media (atmosphere, soil, marine and fresh surface waters and sediments) and the living organisms (including humans) that interact with them. Climate, surface waters and soils are common to consideration of both the geosphere and biosphere. The biosphere description is limited to those factors that directly affect potential exposure of humans and other flora and fauna to radioactivity.

365 When describing the disposal system, there are two significant sources of uncertainty that need to be taken into account. First, there is uncertainty associated with characterising the system as it is at present. Second, there is uncertainty associated with the future evolution of the disposal system. The system description in [48] relates to the baseline status and the assumed status at closure of D3100. As such, it presents a lot of the information that is contained in Sections 4, 5 and 6 of this ESC and is not repeated here. Assumptions concerning the evolution of the facilities themselves and the potential impacts of climate evolution and other external events are addressed as part of the scenario development process as described below.

7.4 Run 5 PA Scenario Development (FEP Analysis) and Calculation Cases

GRA 6.2.31	All engineered measures will degrade with time and this should be recognised in the environmental safety case.
GRA 6.4.11	Identify the presence of any actually or potentially valuable resources near the site and make an assessment of the extent to which the site and its surroundings might be disturbed as a result. Consider the implications for the integrity of the disposal system.
GRA 7.2.1(a)	The environmental safety case should demonstrate a clear understanding of the disposal facility in its geological setting ("the disposal system") as it evolves.

GRA 7.2.8(c)	After the period of authorisation and while any significant hazard remains, the environmental safety case should explore the consequences not only of the expected evolution of the disposal system, but also of less likely evolutions and events.
GRA 7.3.28	Quantitative modelling projections should not be made for times so far into the future that uncertainties make the modelling results lose any meaning.
GRA 7.3.32	Take into account the potential for climate change. There is considerable uncertainty regarding the rate, amount and even the direction of possible climate change over different timescales, so consider a range of possibilities. The potential consequences of climate change include changes in rainfall patterns (which can affect watercourses and aquifers), changes in sea level, increased rates of erosion including coastal erosion, glacial cycling and glaciotectonic movements.
GRA 7.3.33	Consider human intrusion as part of the environmental safety case - because of the associated uncertainty, this is likely to involve using stylised calculations.
GRA 6.3.41(a)	Do not consider human intrusion where the intruders have full knowledge of the existence, location, nature and contents of the disposal facility.
GRA 6.3.41(b)	Consider human intrusion in cases where there is no prior knowledge of the disposal facility or where there is knowledge of the existence of underground workings but no understanding what they contain.
GRA 6.3.47	Explore the timing, type and extent of human intrusion into a facility through one or more 'what-if' scenarios, separate from the scenarios representing evolution of the disposal system undisturbed by human intrusion.
GRA 6.3.48(a)	Human intrusion scenarios should be based on human actions that use technology and practices similar to those that currently take place, or that have historically taken place, in similar geological and geographical settings anywhere in the world. The assumed habits and behaviour of people should be based on present and past human habits and behaviour that have been observed and are judged relevant.
GRA 6.3.48(b)	Human intrusion scenarios should include all human actions associated with any material removed from the facility, including considering what is then done with this material. When considering optimisation, the number of people involved in actions associated with intrusion should be assessed, and may be assumed to be similar to the typical number involved in similar actions now or historically. Similarly, the number of people who might be exposed as a result of occupying the site or neighbourhood after the intrusion should also be assessed. Each scenario considered should be substantiated as being reasonable and suited to the particular circumstances.
GRA 6.3.55	Show that intrusion by non-human species, including plant species (for example tree roots), is not a significant issue.

7.4.1 Scenario development methodology

366 All radioactive waste disposal programmes face the challenge of determining which phenomena and components of the disposal system can and should be represented in the quantitative PA. In the radioactive waste disposal literature, this problem is

normally referred to as "scenario development", and the phenomena and components of the system are usually referred to as features, events and processes (FEPs). The GRA [19] defines a scenario as "*a postulated or assumed set of conditions and/or events*". Scenarios can be considered as broad descriptions of alternative futures of the waste disposal system. Multiple scenarios may be defined where it is not possible or convenient to describe the system using a single integrated model.

367 The main objectives for scenario development are to [283]:

- Demonstrate or try to ensure completeness or sufficiency in the scope of a PA.
- Decide which FEPs to include in a PA and how to treat them.
- Provide traceability from data and information to the PA scenarios, models, parameter values, and calculation cases.
- Structure the PA calculations.
- Promote transparency and improve comprehensibility of the PA and the PA results.
- Guide decisions concerning future work.

368 There is no one approved methodology for conducting scenario development for radioactive waste management PAs. Each PA practitioner develops its methodology to meet its own needs, while taking into account the objectives set out above. The scenario development methodology adopted for the D3100 project PA is consistent with the methodology set out by an NEA Working Group [284] and involves four steps:

- Identification and classification of all phenomena (i.e. FEPs) potentially relevant to the performance of the disposal system.
- Elimination of phenomena from calculations of performance according to well-defined screening criteria.
- Identification or formation of scenarios relevant to the performance of the disposal system.
- Specification of scenarios for performance analysis.

369 A full scenario development process was undertaken for Runs 1, 2 and 3. The full process was not repeated for Runs 4 and 5; rather the scenarios considered in Runs 4 and 5 are based largely on the FEP analysis and development of the scenarios undertaken for Run 3 [278], but with review of the FEP screening in light of any new information and the developing context of the PA. The first two steps of the scenario development process, as undertaken for the Run 3 PA, are described in Section 7.4.2, and the second two steps and the resulting scenarios for the Run 5 PA are described in Section 7.4.3. For the D3100 project PA, two main classes of scenario are defined:

- An Undisturbed Performance scenario based on the retained FEPs that are likely to occur over the assessment timeframe but that do not physically disrupt the waste disposals.
- Disturbed Performance scenarios, distinguished by the consideration of one or more retained FEPs that have an uncertain likelihood of occurrence over the assessment timeframe and whose impact would bypass or eliminate at least one of the disposal system barriers. For Run 5, a further distinction has been made to identify those Disturbed Performance FEPs that are very low likelihood and are therefore treated as "what-if" calculations only.

7.4.2 FEP identification and FEP screening

370 The identification of FEPs to be considered is an activity common to all PAs of long-term safety of radioactive wastes, although the formality with which this activity is done and documented varies considerably. However, formal documentation of the identification of relevant FEPs, and recording of information related to each FEP, can have several benefits [285]:

- Development of a FEP list provides an opportunity for discussion amongst the project team and independent experts to identify the relevant FEPs.
- Descriptive information and references added against each FEP provides a source of information that can be used during scenario and model development activities.
- A FEP list and database provide a framework to record information about a FEP, and whether or not the FEP is included in PA models.
- The models used in a PA can be audited against the list of FEPs with a view to ensuring that all important processes are included, or to assist in specifying further model developments or data acquisition.
- Clear description of each FEP, its relevance, and how it has been treated in the PA, generates confidence in the logic and thoroughness of the PA.

371 A comprehensive list of potentially relevant FEPs was developed for Run 1 to be screened by both PA contractors to define and document the scope of their respective PAs. Version 1 of the Dounreay LLW FEP List was based on the Version 1 International FEP list for geological disposal developed by the NEA in 2000[27] [285] to represent a comprehensive master list of FEPs relevant to the assessment of long-term safety of solid radioactive waste repositories. The NEA Version 1 International FEP List was also adopted by the IAEA ISAM Project [64] with minor modifications, which were considered in the development of Version 1 of the

[27] Note that the NEA International FEP list has since been updated to include reference to more recent project-specific assessments. The latest issue, Version 3, which focuses on deep geological disposal, was published in July 2019. It has not been considered necessary to update the Dounreay FEP list in response to the update of the NEA list, partly because keeping the existing structure promotes transparency between iterations of the D3100 PA and partly because the existing structure aligns better with the ISAM International FEP List for near-surface disposal.

Dounreay LLW FEP List [286]. The Dounreay LLW FEP List is structured as follows [286]:

- The Assessment Basis FEPs (Group 0 in the International FEP List) are numbered from 1.01 to 1.10 in the Dounreay LLW FEP List. These FEPs provide the constraints on, and overall scope of, the PA – they do not relate directly to factors that might affect the behaviour of the disposal system. As such, these FEPs provide the background for screening other FEPs for inclusion in the PA models.
- The Repository Issues FEPs (Group 1.1 in the International FEP List) are numbered from 2.01 to 2.13 in the Dounreay LLW FEP List. These FEPs describe the disposal concept and facilities planning, construction, operation, and closure issues. As for the Assessment Context FEPs, the Repository Issues FEPs do not relate directly to factors that may or may not need to be modelled in the PA. Therefore, these FEPs have been extracted as a separate group of FEPs for the Dounreay FEP list, providing background for screening other FEPs.
- The remaining FEPs are kept in the NEA groupings of External Factors (3.1 to 3.4 in the Dounreay LLW FEP List), Environmental Factors (4.1 to 4.4 in the Dounreay LLW FEP list), and Radionuclide/Contaminant Factors (5.1 to 5.3 in the Dounreay LLW FEP List). These FEPs have been screened for inclusion in the D3100 PA as set out below. Several of the FEPs in the International FEP List have been subdivided to screen key issues under each FEP in more detail.

372 Version 1 of the Dounreay LLW FEP List was also used for the 2006 PA of the Shaft [287], which reviewed the list for completeness and no additional FEPs were identified. Version 1 of the Dounreay FEP List [286], as modified during Run 1 [288], was adopted as Version 2 of the Dounreay FEP List to form the basis for the Run 2 PA. Similarly, the Dounreay LLW FEP List was updated to Version 3 for the Run 3 PA [278, App.1].

373 As noted above, in the Dounreay LLW FEP List, Assessment Basis (Category 1) and Repository Issues (Category 2) FEPs set the scope and background for the PA and do not require screening for inclusion in the PA. The remainder of the FEPs in the FEP List (Categories 3, 4 and 5) were re-screened for Run 3 to ensure that the screening arguments developed in Runs 1 and 2 remained valid. The screening process is illustrated in Figure 7.2. The screening decision for each FEP can be:

- Category O: Certain FEPs can be excluded from the PA on the basis that they are **O**utside the scope of the PA.
- Category SO-P: FEP is **S**creened **O**ut of the PA calculations on the basis of low **P**robability of occurrence over a timescale of significance to the calculated performance of the disposal system (i.e. on the order of 100,000 years or up to disruption of the facilities by natural processes).
- Category SO-C: FEP is **S**creened **O**ut of the PA calculations on the basis of having a low **C**onsequence to the calculated performance of the disposal system. Several of these screening decisions can be made by reference to

the results of previous iterations of the PA. The probability and consequence screening arguments can be linked if, for example, a FEP of a certain magnitude has to occur before it is significant to performance.

- Category UP: FEP is expected to occur, has a significant contribution to the performance of the system, and is accounted for in the **U**ndisturbed **P**erformance scenario. FEPs screened as UP are also generally included in the modelling of the Disturbed Performance scenarios, at least up to the time of disturbance. The Undisturbed Performance scenario is broadly equivalent to the Design scenario in the ISAM methodology [64].
- Category DP: FEP is included in calculations of **D**isturbed **P**erformance, since it is not certain to occur within a specific timeframe and, if it does occur, the effect on the disposal system is to bypass or eliminate one or more disposal system barriers.

374 No specific constraint on the quantification of the low consequence and low probability screening decision has been applied in the D3100 PA. The screening arguments detail the judgements in each case and provide the basis for the decisions reached. The screening decisions for the Run 3 PA are summarised in Table 7.1.

375 Both the Run 4 and Run 5 PAs have used the formal FEP analysis undertaken for the Run 3 PA as the basis for scenario development. In the Run 4 PA, all of the Run 3 screening decisions were unchanged [279, §4]. Similarly, most of the screening decisions remain the same for Run 5. However, a high-level review of the Dounreay LLW FEP List identified two UP FEPs, hydrological/hydrogeological response to climate change and large scale geosphere discontinuities, and one DP FEP, glacial and ice sheet effects, that could be screened out for Run 5. This is on the basis of qualitative arguments and the Run 3 and 4 PA results which showed them to be of low consequence. The justifications for these changes are detailed in the Run 5 PA [48, §4.3.1]. The screening decisions for Run 5 are shown in Table 7.1.

376 The Dounreay LLW FEP list and the screening of the FEPs will continue to be revisited before each future iteration of the PA.

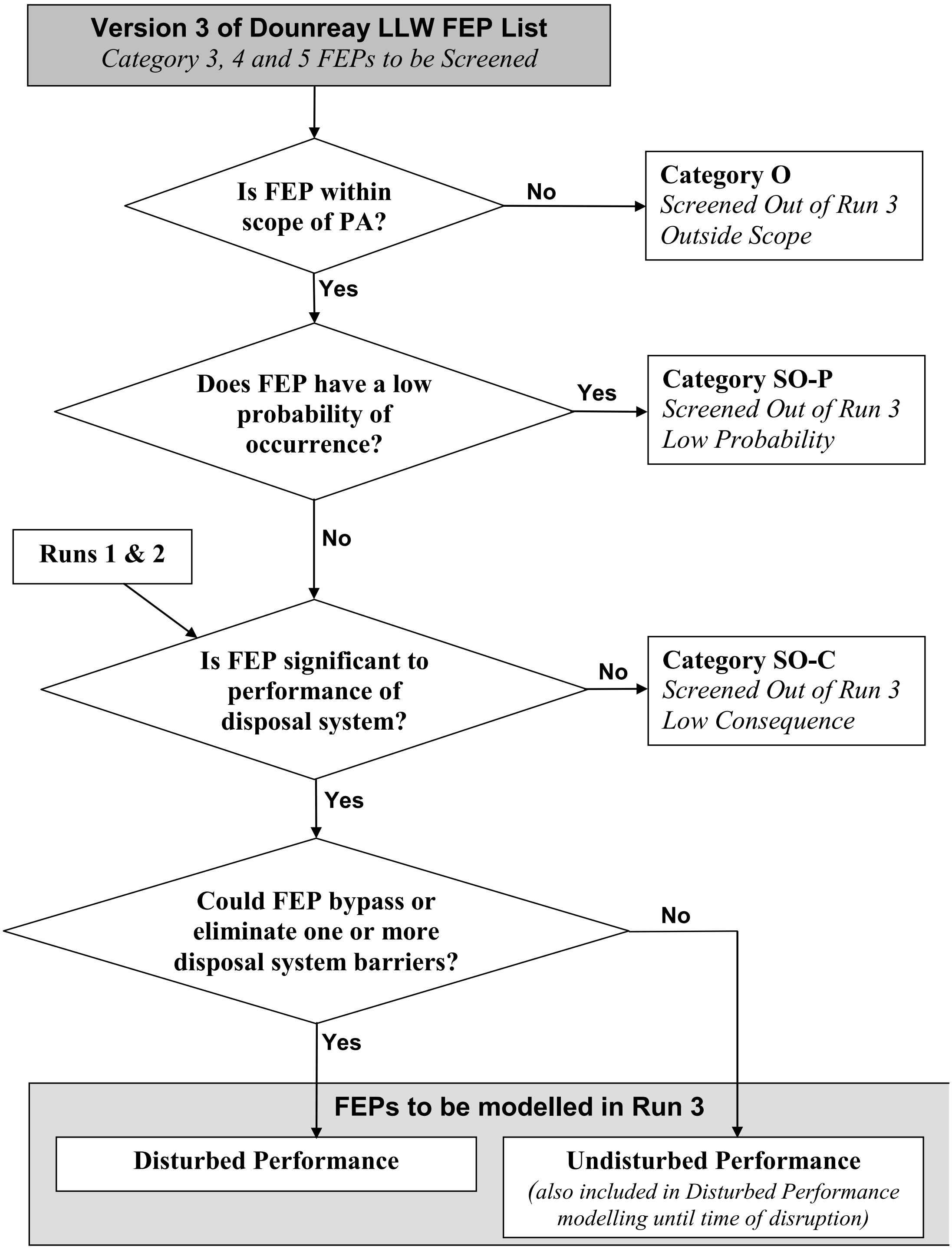

Figure 7.2: FEP screening process for the Run 3 PA [278]. The “Runs 1 & 2” box indicates input of learning from previous iterations of the PA.

Table 7.1: Summary of FEP screening decisions for the Run 3 PA [see 278, App.1] and the results of the review conducted for Run 5 (only changes from Run 3 are identified). FEP titles in italics are sub-divisions of the numbered NEA 2000 International FEPs.

FEP No.	FEP Title	Run 5 Review	Run 3 Screen.
1	**Assessment Context**		
1.01	Impacts of concern		*No Screening*
1.02	Timescales of concern		
1.03	Spatial domain of concern		
1.04	Repository assumptions		
1.05	Future human action assumptions		
1.06	Future human behaviour (target group) assumptions		
1.07	Dose response assumptions		
1.08	Aims of the assessment		
1.09	Regulatory requirements and exclusions		
1.10	Model and data issues		
2	**Repository Issues**		
2.01	Site investigation		*No Screening*
2.02	Excavation/construction		
2.03	Emplacement of wastes and backfilling		
2.04	Closure and repository sealing		
2.05	Records and markers, repository		
2.06	Waste allocation		
2.07	Repository design		
2.08	Quality control		
2.09	Schedule and planning		
2.10	Administrative control, repository site		
2.11	Monitoring of repository		
2.12	Accidents and unplanned events		
2.13	Retrievability		
3	**External Factors**		
3.1	**Geological Processes and Effects**		
3.1.01	Tectonic movements and orogeny		SO-P
3.1.02	Deformation, elastic, plastic or brittle		SO-P
3.1.03	Seismicity *faulting/rupture* *tsunami*		 *DP* *SO-C*
3.1.04	Volcanic and magmatic activity		SO-P
3.1.05	Metamorphism		SO-P
3.1.06	Hydrothermal activity		SO-P
3.1.07	Erosion and sedimentation		DP
3.1.08	Diagenesis		SO-P
3.1.09	Salt diapirism and dissolution		O
3.1.10	Hydrological/hydrogeological response to geological changes		SO-C
3.2	**Climatic Processes and Effects**		
3.2.01	Climate change, global		UP
3.2.02	Climate change, regional and local		UP
3.2.03	Sea-level change		UP
3.2.04	Periglacial effects		SO-C
3.2.05	Glacial and ice sheet effects, local	SO-C	DP
3.2.06	Warm climate effects (tropical and desert) *warm climate and desert climate* *storm surges*		 SO-P SO-C
3.2.07	Hydrological/hydrogeological response to climate changes	SO-C	UP

FEP No.	FEP Title	Run 5 Review	Run 3 Screen.
3.2.08	Ecological response to climate changes		SO-C
3.2.09	Human response to climate changes		SO-C
3.3	**Future Human Actions**		
3.3.01	Human influences on climate		UP
3.3.02	Motivation and knowledge issues (inadvertent/deliberate human actions)		DP
3.3.03	Un-intrusive site investigation		O
3.3.04	Drilling activities including fracking (human intrusion)		DP
3.3.05	Mining and other underground activities (human intrusion)		SO-P
3.3.06	Surface environment, human activities		DP
3.3.07	Water management (wells, reservoirs, dams) *surface water management* *groundwater extraction*		 *UP* *DP*
3.3.08	Social and institutional developments		O
3.3.09	Technological developments		O
3.3.10	Remedial actions		O
3.3.11	Explosions and crashes		DP
3.4	**Other**		
3.4.01	Meteorite impact		SO-P
3.4.02	Species evolution		O
3.4.03	Miscellaneous and FEPs of uncertain relevance		O
4	**Disposal System Domain: Environmental Factors**		
4.1	**Wastes and Engineered Features**		
4.1.01	Inventory, radionuclide and other material *radionuclide inventory – LLW and Demolition LLW* *other material inventory – LLW and Demolition LLW*		 *UP* *UP*
4.1.02	Wasteform materials and characteristics *hydrological and mechanical characteristics – LLW and Demolition LLW* *chemical characteristics – LLW and Demolition LLW* *cracking – LLW* *waste heterogeneity – LLW and Demolition LLW*		 *UP* *UP* *UP* *SO-C*
4.1.03	Container materials and characteristics *container failure – LLW* *hydrological and mechanical characteristics – LLW* *chemical characteristics – LLW* *containers – Demolition LLW*		 *UP* *SO-C* *UP* *SO-C*
4.1.04	Buffer/backfill materials and characteristics *hydrological characteristics – LLW* *mechanical characteristics – LLW* *chemical characteristics – LLW* *backfill – Demolition LLW*		 *UP* *SO-C* *UP* *SO-C*
4.1.05	Seals, cavern/tunnel/shaft *hydrological characteristics – LLW and Demolition LLW* *mechanical characteristics – LLW and Demolition LLW* *chemical characteristics – LLW and Demolition LLW*		 *UP* *SO-C* *UP*
4.1.06	Other engineered features materials and characteristics *drainage system* *hydrological characteristics – floors and walls* *mechanical characteristics – floors and walls* *chemical characteristics – floors and walls*		 *SO-C* *UP* *SO-C* *UP*
4.1.07	Mechanical processes and conditions (in wastes and Engineered Barrier System (EBS))		SO-C
4.1.08	Hydraulic/hydrogeological processes and conditions (in wastes and EBS)		UP

FEP No.	FEP Title	Run 5 Review	Run 3 Screen.
4.1.09	Chemical/geochemical processes and conditions (in wastes and EBS) *chemical conditioning – LLW* *chemical conditioning – Demolition LLW* *dissolution and sorption* *organic complexation* *precipitation and co-precipitation* *redox* *radiolysis and galvanic coupling* *chemical heterogeneity*		 *UP* *SO-C* *UP* *SO-C* *SO-C* *UP* *SO-C* *SO-C*
4.1.10	Biological/biochemical processes and conditions (in wastes and EBS) *microbial degradation* *chemical effects* *radionuclide binding*		 *UP* *UP* *SO-C*
4.1.11	Thermal processes and conditions (in wastes and EBS)		SO-C
4.1.12	Gas sources and effects (in wastes and EBS) *gas generation* *gas flow* *gas explosions* *radioactive gases* *volatile organic gases*		 *UP* *SO-C* *SO-P* *UP* *SO-C*
4.1.13	Radiation effects (in wastes and EBS)		SO-C
4.1.14	Nuclear criticality		SO-P
4.2	**Geological Environment**		
4.2.01	Excavation disturbed zone, host rock		SO-C
4.2.02	Host rock		UP
4.2.03	Geological units, other		UP
4.2.04	Discontinuities, large scale (in geosphere)	SO-C	UP
4.2.05	Contaminant transport path characteristics (in geosphere)		UP
4.2.06	Mechanical processes and conditions (in geosphere)		SO-C
4.2.07	Hydraulic/hydrogeological processes and conditions (in geosphere)		UP
4.2.08	Chemical/geochemical processes and conditions (in geosphere)		UP
4.2.09	Biological/biochemical processes and conditions (in geosphere)		SO-C
4.2.10	Thermal processes and conditions (in geosphere)		SO-C
4.2.11	Gas sources and effects (in geosphere)		SO-C
4.2.12	Undetected features (in geosphere)		SO-C
4.2.13	Geological resources *groundwater for drinking* *water for irrigation* *flagstones* *other resources*		 *DP* *SO-P* *DP* *SO-P*
4.3	**Surface Environment**		
4.3.01	Topography and morphology		UP
4.3.02	Soil and sediment		UP
4.3.03	Aquifers and water-bearing features, near surface		UP
4.3.04	Lakes, rivers, streams and springs		UP
4.3.05	Coastal features		UP
4.3.06	Marine features		UP
4.3.07	Atmosphere		UP
4.3.08	Vegetation		UP
4.3.09	Animal populations		UP

FEP No.	FEP Title	Run 5 Review	Run 3 Screen.
4.3.10	Meteorology		UP
4.3.11	Hydrological regime and water balance (near-surface)		UP
4.3.12	Erosion and deposition		
	glacial erosion		*SO-C*
	coastal erosion		*UP*
	other erosion processes		*SO-C*
4.3.13	Ecological/biological/microbial systems		UP
4.4	**Human Behaviour**		
4.4.01	Human characteristics (physiology, metabolism)		UP
4.4.02	Adults, children, infants and other variations		SO-C
4.4.03	Diet and fluid intake		UP
4.4.04	Habits (non-diet-related behaviour)		UP
4.4.05	Community characteristics		SO-C
4.4.06	Food and water processing and preparation		SO-C
4.4.07	Dwellings		UP
4.4.08	Wild and natural land and water use		
	wild water use		*UP*
	wild land use		*SO-C*
4.4.09	Rural and agricultural land and water use (incl. fisheries)		
	land agriculture		*UP*
	fisheries		*SO-C*
4.4.10	Urban and industrial land and water use		SO-C
4.4.11	Leisure and other uses of environment		SO-C
5	**Radionuclide/Contaminant Factors**		
5.1	**Contaminant Characteristics**		
5.1.01	Radioactive decay and in-growth		UP
5.1.02	Chemical/organic toxin stability		O
5.1.03	Inorganic solids/solutes		O
5.1.04	Volatiles and potential for volatility		
	radioactive methane, hydrogen and radon		*UP*
	other radioactive-bearing volatile species		*SO-C*
5.1.05	Organics and potential for organic forms		
	volatile organic species		*SO-C*
	dissolved organic species		*SO-C*
	solid organic species		*SO-C*
5.1.06	Noble gases		SO-C
5.2	**Contaminant Release/Migration Factors**		
5.2.01	Dissolution, precipitation and crystallisation, contaminant		
	dissolution		*UP*
	precipitation		*SO-C*
5.2.02	Speciation and solubility, contaminant		UP
5.2.03	Sorption/desorption processes, contaminant		UP
5.2.04	Colloids, contaminant interactions and transport with		
	near-field colloids		*SO-C*
	geosphere colloids		*SO-C*
5.2.05	Chemical/complexing agents, effects on contaminant speciation/transport		SO-C
5.2.06	Microbial/biological/plant-mediated processes, contaminant		UP
5.2.07	Water-mediated transport of contaminants		
	advection and diffusion		*UP*
	dispersion and matrix diffusion		*UP*
5.2.08	Solid-mediated transport of contaminants		UP

FEP No.	FEP Title	Run 5 Review	Run 3 Screen.
5.2.09	Gas-mediated transport of contaminants *radioactive gases* *fluid flow and transport due to gas production*		 *UP* *SO-C*
5.2.10	Atmospheric transport of contaminants		UP
5.2.11	Animal, plant and microbe mediated transport of contaminants		SO-C
5.2.12	Human-action-mediated transport of contaminants *water use (e.g. irrigation)* *non-intrusive human actions* *intrusive human actions*		 *SO-P* *SO-C* *DP*
5.2.13	Food chains, uptake of contaminants in		UP
5.3	**Exposure Factors**		
5.3.01	Drinking water, foodstuffs and drugs, contaminant concentrations in		UP
5.3.02	Environmental media, contaminant concentrations in		UP
5.3.03	Non-food products, contaminant concentrations in		SO-C
5.3.04	Exposure modes		UP
5.3.05	Dosimetry		UP
5.3.06	Radiological toxicity/effects		UP
5.3.07	Non-radiological toxicity/effects		O
5.3.08	Radon and radon daughter exposure		UP

7.4.3 Scenario specification and calculation cases

377 The following scenarios were identified for consideration in the D3100 project Run 5 PA:

- Undisturbed Performance.
- Disturbed Performance - Inadvertent human intrusion.
- Disturbed Performance - Coastal erosion.
- Disturbed Performance - “What-if” calculations:
  - Groundwater extraction.
  - Ground rupture.

Undisturbed performance

378 As the FEP screening process in Figure 7.2 indicates, FEPs identified for inclusion in the D3100 PA models are categorised as those for inclusion in modelling of undisturbed performance and those for inclusion in modelling of disturbed performance. All of the FEPs identified in the FEP analysis for inclusion in modelling of undisturbed performance are included in a single Undisturbed Performance scenario. An Undisturbed Performance scenario reference calculation is defined using the best estimates for the models and parameter values used to represent the FEPs in the Undisturbed Performance scenario. Further sets of calculation cases are then defined at the alternative model and parameter value levels to address the quantifiable uncertainties in the representation of the FEPs in the Undisturbed Performance scenario [48, Tab.4.3].

379 In the Undisturbed Performance scenario, the near-field engineering degrades gradually through a combination of physical and chemical processes, leading to changes in hydrological, chemical and mechanical properties. Radioactivity decays and is either retained in the near-field until decay or is released via gas or groundwater phases. Releases via groundwater migrate through the geosphere through different pathways to the biosphere. Releases via gas phases are assumed to be directly to the biosphere.

380 For the near-field, geosphere and biosphere, uncertainties are generally related to chemical or hydrological properties, or degradation rates. For climate change, uncertainties relate to the consequences of changes on coastal erosion rates. However, the same general sequence of climate change has been assumed for all of the Undisturbed Performance scenario calculation cases:

- Global warming with sea-level rise and coastal erosion.
- Extended warm period with slightly higher rainfall than present, high sea-levels and further coastal erosion.
- Stable sea level and a climate similar to the present day, with a cessation of coastal erosion.
- Gradual cooling to colder boreal climate conditions, with falling sea level.
- Severe cooling to periglacial conditions.

381 Erosion of the geosphere between the facilities and the coast is considered in the Undisturbed Performance scenario. However, the combination of the coastal erosion rate and the duration of warmer climate conditions under which erosion occurs are considered to be not sufficient to completely remove the geosphere barrier and erode the facilities in the Undisturbed Performance scenario. The complete destruction of the geosphere and near-field barriers by coastal erosion, leading to disruption of the wastes themselves, is considered as a Disturbed Performance scenario.

382 Regarding the timescales of the assessment, the Undisturbed Performance scenario extends until the peak or maximum calculated annual risk to the potential RPs has passed and any continuing risk is insignificant. Calculations have been run to 100,000 years into the future, and the peak risk from the natural groundwater pathway is calculated to have been passed by this point (see Figure 7.10).

Disturbed performance

383 Table 7.1 shows the FEPs screened in [48] for inclusion in the Disturbed Performance scenarios. These FEPs have been grouped on the basis of similar disruption characteristics into the following Disturbed Performance scenarios [48, Tab.4.2]: inadvertent human intrusion; coastal erosion; groundwater extraction and ground rupture. A further screening of the disturbed performance FEPs for Run 5 identified two of these scenarios, groundwater extraction and ground rupture, being considered as “what-if” calculations. Further details on this exercise are provided in [48, §4.3.1].

384 Several FEPs in Table 7.1 are grouped under the inadvertent human intrusion Disturbed Performance scenario. Based on analysis of present-day practices and

technologies in the Dounreay area [19, ¶6.3.48], activities that might lead to inadvertent disruption of the cap and wastes of D3100 include:

- Quarrying for flagstones or rock or concrete from the vaults.
- Drilling and small-scale investigation and excavation activities for farming and in advance of other activities.
- Residential, industrial, leisure and transport construction activities.

385 There are no resources in the vicinity of D3100 that are likely to provide incentives for quarrying at the site in particular, compared to anywhere else in the region (Section 6.2.6). Quarrying tends to be aimed at particular beds where they are known to occur near the surface. However, the possibility of localised disruption during digging by a farmer for flagstones, or indeed for vault concrete, cannot be completely ruled out. Furthermore, residential or industrial developments or archaeological investigations at the site cannot be discounted in the future, when knowledge of D3100 has been lost. The waste in D3100 will be at least 4 m below ground level and, therefore, is unlikely to be disturbed directly by construction activities. Foundations for domestic and light buildings are typically 1 or 2 m deep and pits (e.g. cess pits) might be excavated to depths of a few metres [289]. Commercial wind-farms do not require excavation of deep foundations; they tend to use raft foundations that are 2 to 3 m deep [289]. However, drilling of investigation boreholes could lead to exhumation of waste materials. Adjacent and/or subsequent users of the site, such as residents or workers, could be exposed to spoil left on completion of the investigation.

386 The likelihood and nature of any inadvertent intrusion are hard to define. For this reason, the D3100 project PA follows the advice in the GRA [19] and uses stylised scenarios to assess the consequences of inadvertent human intrusion. A set of stylised scenarios grouped under the banner of inadvertent human intrusion has been specified for the Run 5 PA based on advice to SEPA from the HPA in 2011 on scenarios relevant to the post-closure safety of a purpose-built facility for radioactive waste located a few tens of metres below ground level [290]. The HPA reviewed other assessment studies and determined the relevance of intrusion scenarios to the scope specified by SEPA. They also reviewed the ISAM FEP list, which is consistent with the D3100 FEP list. The HPA identified a list of eleven inadvertent intrusion scenarios that was consolidated into five stylised inadvertent intrusion scenarios, with a total of eight representative exposed groups. Four of the five scenarios put forward by the HPA are considered in the Run 5 PA:

- Intrusion during borehole investigations.
- Intrusion by quarrying.
- Exposure during direct investigations of the vaults by an archaeologist.
- Exposure during direct investigations of the vaults by a curious worker.

387 Only the HPA scenario of tunnelling is not modelled in the Run 5 PA, as such a scenario is not applicable at the shallow depth of D3100. These scenarios bound the potential consequences of any other possible intrusion associated with possible

human activities (e.g. site investigation during redevelopment as a residential area, leisure complex, for road building, etc.).

388 During borehole investigations, a geotechnical engineer is assumed to be exposed to radionuclides as a result of inhalation of contaminated dust, ingestion of contaminated dust, skin contamination and external irradiation from contaminated material that is left on the ground and the core sampled during excavation activities. A truck or digger driver might be exposed when transporting material from the borehole. A resident is assumed to use land into which spoil has been mixed following borehole investigations and subsequent development. Doses to a quarry worker are assumed to occur through skin contamination, external exposure, inhalation, and inadvertent ingestion of contaminated material in the air at the quarry. A resident downwind of the quarry may receive a dose through ingestion of crops grown in a garden contaminated by dust from the quarrying.

389 The controlled intrusion scenario concerns the situation where some event (for example, quarrying) has partially uncovered the vaults or resulted in the presence of D3100 being recognised. However, the nature of D3100 is not understood. Professional help is sought and subsequently an investigation takes place. This involves taking small samples from the waste. This scenario therefore represents a form of deliberate intrusion, when controls on work practices (for example, rules and regulations) are enforced, but the worker is unaware of the nature of the D3100. The uncontrolled intrusion scenario considers a similar situation, but where the presence of the uncovered vaults arouses curiosity rather than professional investigation. Once discovered, D3100 is broken into using locally obtained tools by a curious worker. The worker then spends a limited amount of time investigating the contents of the vaults by hand, including picking up objects. After this time the worker is assumed to either not find anything of interest (so they then rebury the wastes or just move on) or report the discovery (probably prompting a formal investigation by experts).

390 The IAEA ISAM Project FEP List [64] has a specific entry for intrusion by burrowing animals or plants. The lack of trees growing on the coastal plain at Dounreay and the depth of the waste at least 4 m below the ground surface protected by a cap designed to deter human intrusion makes either possibility unlikely. The Run 3 FEP analysis considered that the impact of flora and fauna on the cap was covered in the cap degradation uncertainty analysis under the Undisturbed Performance scenario.

391 For all considered inadvertent human intrusion Disturbed Performance scenarios, the calculations consider the disruptive event occurring in each year after closure out to 50,000 years and the exposure occurring during or immediately after intrusion. However, by this time the results of the human intrusion calculations are considered to be highly pessimistic due to the absence of leaching in the model (see Section 431).

392 In regards to the other Disturbed Performance Scenarios:

- Coastal Erosion. It is possible that an extended period of high sea level and/or an increase in erosion rates could lead to complete erosion of D3100. This is modelled in the Run 5 PA as a coastal erosion Disturbed Performance scenario. The scenario assumes the same processes operating today continue until the vaults are totally eroded onto the foreshore and subsequently into the sea. Uncertainty in the erosion rates is considered by undertaking separate PA calculations with different erosion rates.

- Ground Rupture. D3100 has been constructed in the vicinity of several faults of varying sizes. There is no evidence of recent movements on these faults [196]. Further, earthquakes that do occur in Britain are not generally large enough to cause ground rupture in buildings. However, while highly unlikely, the possibility of movement on a fault causing come damage to the facilities' engineering over the next hundred thousand years cannot be ruled out. In the Run 5 PA, fault movement and rupture of engineering is considered as a "what-if" Disturbed Performance scenario. This considers movement on one or more faults near or beneath the facilities causing rupture of the barriers around the vaults and cracking of the grouted LLW after active institutional control has ceased.
- Groundwater Extraction. Sinking of a well or borehole to abstract water for drinking would bypass and disturb the natural barrier provided by the geosphere at the D3100 site and so is classed has a Disturbed Performance scenario. However, the scenario is extremely unlikely. First, there is an affordable public water supply system. Second, if the public supply ceases to be available or becomes too expensive, there is abundant surface water and precipitation (rainfall) from which to extract supplies. Third, in the unlikely event that a borehole/well is sunk for abstraction purposes, it would probably be sunk away from the coastline and to very shallow depths or to depths below the zone of potential groundwater contamination, probably down to the Fresgoe Sandstone where significant flows and artesian conditions are likely to be encountered. Nonetheless, the Run 5 PA considers the potential consequences of a borehole/well being sunk downstream of the facilities in a stylised "what-if" Disturbed Performance scenario. In this scenario, drinking water and water for livestock are abstracted from a borehole/well located in the groundwater zone with the highest levels of contamination from the facilities (drinking of contaminated surface water by livestock is considered in the Undisturbed Performance scenario).

393 As for the Undisturbed Performance scenario, calculations for the Disturbed Performance scenarios considering ground rupture, coastal erosion and ground water extraction are extended until the peak or maximum calculated annual dose/risk to the potential RPs has passed following the disruptive event.

Scenarios not considered in the Run 5 PA

394 The scenarios described above cover those assessed for the previous D3100 project PAs, except for disruption by a tsunami considered by EQ in Run 1 [158], and glaciation considered in Runs 1 to 4 [279].

395 As discussed in Section 6.3.1, while tsunamis may occur in the future, they are unlikely to be of sufficient magnitude to disrupt the wastes some 4 m or more below the ground surface. In any event, the potential consequences of a major tsunami were shown to be bounded by the large-scale inadvertent human intrusion scenario considered in Run 1 [158].

396 The effects of glacial conditions were considered in the Run 3 and 4 PAs in terms of gross impact, with disruption of the site by an ice sheet assessed as a Disturbed Performance scenario. However, rather than attempting a highly subjective calculation, these assessments used the Run 3 large-scale inadvertent human intrusion stylised scenario as a bounding case. Results for large-scale human intrusion, which used a 1:10 dilution, considered at 100,000 years after closure reported relatively low doses [279, ¶296-297]. Doses from glacial disruption would be much lower owing to the wider spread of material (greater dilution) and the fact leaching will have occurred given that the next glaciation will be significantly later than 100,000 years (Section 6.3.4). Given the low doses indicated by reference to the Run 3 human intrusion results, it was not considered proportionate to further develop the analysis of glacial disruption for Run 5, and this FEP has therefore been screened out of Run 5 on the basis of having a low consequence to the calculated performance of the disposal system (SO-C – Section 7.4.2) [48, §4.3.1].

397 As an additional check for comprehensiveness, the scenarios identified for the Run 3 PA were audited in [278] against a list of scenarios modelled in assessments for other LLW facilities worldwide [64], and no gaps were identified.

7.5 Run 5 PA Models

GRA 7.3.24	Models and associated parameter values should, to the extent possible at the time of the assessment, be site-specific. The use of generic or default data instead of site-specific data should be supported by considering the effect that this has on the ESC.
GRA 7.3.22(a)	Each specific set of modelling studies needs to have specific defined and documented objectives: − modelling objectives should take account of the decisions that the results are intended to support; − the selected approach should be driven mainly by the modelling objectives, and not by the availability of models or software or by considering what models or software were used previously (unless there is an overriding need for consistency); − modelling objectives should be defined in terms of what can be accomplished with the available data. Complex models should not be developed if there is not enough data to support them; − the objectives should be reviewed throughout the modelling process.

7.5.1 Near-field conceptual models

Near-field flow

398 Each of the main disposal vaults in the design (LLW Phases 1 to 3 and Demolition LLW Phases 1 and 2) is represented separately in the Run 5 PA model. This allows consideration of inventory distribution (e.g. allocation of the LLW Pits wastes to LLW Phase 3) and consideration of impacts from each component of the disposal system (e.g. separate assessments for LLW and Demolition LLW impacts). The inventories considered in the reference calculations in Run 5 are the 2020 Case B and Demolition LLW best estimate reported in Section 4.3 [47].

399 In the PA model of the LLW vaults, the waste is divided into four layers with thin interlayers (Figure 7.3). This provides a simple representation of different flow paths through the vaults to investigate the potential consequences of faster pathways through the waste (for example, either though penetrative cracking or through use of a more permeable backfill). The waste in the PA model of the Demolition LLW vaults is represented as a single block surrounded by the walls and floor.

400 Directly overlying the wastes in the PA model is a low-conductivity layer representing the vault lid. This is overlain by a higher-conductivity layer that connects with the enhanced geosphere and reinstates the near-surface higher volume flow system in the very near-surface (in reality this layer will also be designed to act as a deterrent to inadvertent human intrusion). In turn this is overlain by a final soil layer.

401 Radionuclides can be transported by advection in the flowing groundwater or by diffusion along concentration gradients. Radionuclides are released either through the downstream barrier into the Devonian groundwater layer or, to a lesser degree, upwards through the cap.

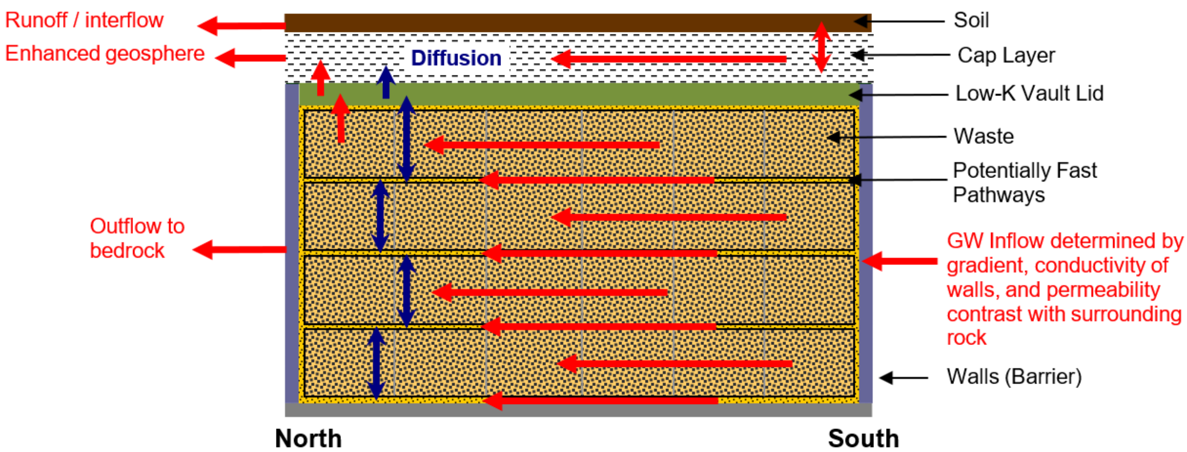

Figure 7.3: Schematic representation of an LLW vault in the Run 5 PA model [48]. Waste is divided into four layers, with the potential for definition of fast or preferential pathways between the layers. Red arrows show advective flow paths and blue arrows show diffusive paths. K = hydraulic conductivity. Representation of Demolition LLW vaults are similar, except the waste is a single block and is not layered.

402 The concrete barriers and wasteforms in D3100 are expected to degrade slowly through a combination of physical, chemical and mechanical processes. However, individual degradation processes are not modelled. Rather, an estimate of the overall effect of degradation and cracking over time on the hydraulic conductivity of each near-field component is made.

Near-field chemistry

403 In the LLW vaults, the water chemistry will be conditioned to a high pH by reaction with the concrete structures, grout backfill and grouted wasteform. Cement conditioning will dominate over the potential effects of any other near-field chemical

components (e.g. corrosion products). Three stages for the evolution/degradation of cement have been defined [177, ¶21]:

- Stage 1: Leaching of alkali metal hydroxides and creation of pH > 13.
- Stage 2: Dissolution of portlandite and pH = 12.5.
- Stage 3: Dissolution of CSH phases and pH decreasing to 10.5.

404 Beyond Stage 3, the pH in the LLW vaults may still remain high owing to dissolution of the degradation products of the grout (e.g. brucite and calcite). However, eventually the pH will decrease to the more neutral pH of the infiltrating groundwater (see pH range in Table 6.7). In terms of radionuclide sorption behaviour, the transitions from Stage 2 to Stage 3 and from Stage 3 to neutral pH are the most important [291]. Therefore, the Run 5 PA model accounts for the timing of the change from Stage 2 to Stage 3 (pH drops below 12.5) and the overall duration of alkaline conditions in the LLW vaults (Stage 3; pH > 10). The estimated timescales for the pH stages used in Run 5 are based on leaching calculations considering the cement inventory and the groundwater flux though the facilities [177, Tab.2.4]. Sorption coefficients are assumed to change linearly across the stages. Run 1 showed that few radionuclides in LLW exhibit strong solubility controls. Therefore, for simplicity, the Run 5 PA assumes only a single step change in solubility controls at the end of Stage 3.

405 In contrast to the LLW vaults, the Demolition LLW will not be conditioned using cementitious grout. Although a proportion of the Demolition LLW will comprise concrete and rubble, it is unlikely that this material will have a strong effect on pH because the waste is likely to have a high bulk porosity and hydraulic conductivity so that water flowing through the waste will encounter much less cementitious material compared to the LLW vaults. The pH in the Demolition LLW vaults is assumed to be weakly alkaline initially, and then start to reflect the composition of incoming groundwater (i.e. around neutral) as the barriers around the vaults degrade and flow through the waste increases. This is a cautious modelling assumption as it reduces the potential for retardation of actinides in the Demolition LLW vaults. Sorption values are assigned to the wasteform and these values are assumed to change linearly to final values as the waste is gradually dissolved. Solubility controls will not be present in the Demolition LLW vaults, although solubility parameters for the neutral pH environment are supplied to the PA model.

406 The redox environment in the facilities will likely vary, both spatially and temporally. Infiltrating waters may be oxidising or reducing, depending on depth, although reducing groundwaters seem more prevalent at the depth of the vaults. Microbial degradation processes and corrosion processes will also act to generate reducing conditions in the near-field vaults, particularly shortly after closure when these processes will be at their fastest. The Run 5 PA model therefore assumes reducing conditions exist in the near-field of the LLW and Demolition LLW vaults following closure. However, an assumption of oxidising conditions is more cautious with an associated increase in solubility and lowering of retardation. The PA assumes conditions become more oxidising after around 10,000 years as the waste degradation and microbial processes in the near-field slow.

407 Radionuclides will dissolve on contact with porewater in the grouted wasteform. For the groundwater pathway calculations, the Run 5 PA conservatively assumes that this dissolution is instantaneous up to a concentration that is determined by a solubility limit for each radionuclide and the extent to which dissolved radionuclides sorb on the waste matrix. The Run 5 PA also includes an empirical factor that delays contaminant releases until the facilities are assumed to have resaturated and waste containers are assumed to have been breached.

7.5.2 Geosphere conceptual models

Terrestrial environment

408 A single geosphere path running northwards between the facilities and the coast is modelled. Two separate paths, covering releases from the LLW vaults and the Demolition LLW vaults, were considered in Run 2 and Run 3. However, the two paths were next to each other and essentially contiguous; therefore, the geosphere model was reduced to one path in Run 4 and the results from the one path and two path implementations were compared to ensure that the revision did not introduce any unforeseen changes [279].

409 Between the vaults and the present-day coast, the geosphere path has been discretised in the Run 5 PA model into five compartments of equal length and width in the horizontal direction along the path and into five layers vertically (Figure 7.4):

- The top soil and cover (around 0.45 m thick).
- The enhanced geosphere (around 4 m thick).
- The near-surface weathered bedrock (around 4 m thick).
- The upper and lower unweathered bedrock layers (around 10 m thick and 15 m thick, respectively).

410 The vertical layers reflect the hydrogeological conceptual model shown in Figure 6.13, but with the addition of the enhanced geosphere in place of the Quaternary cover. The unweathered bedrock is modelled as an upper layer and a lower layer in order to represent coastal erosion, which has the effect of advancing the cliff face closer to the facilities by eroding the upper unweathered bedrock layer.

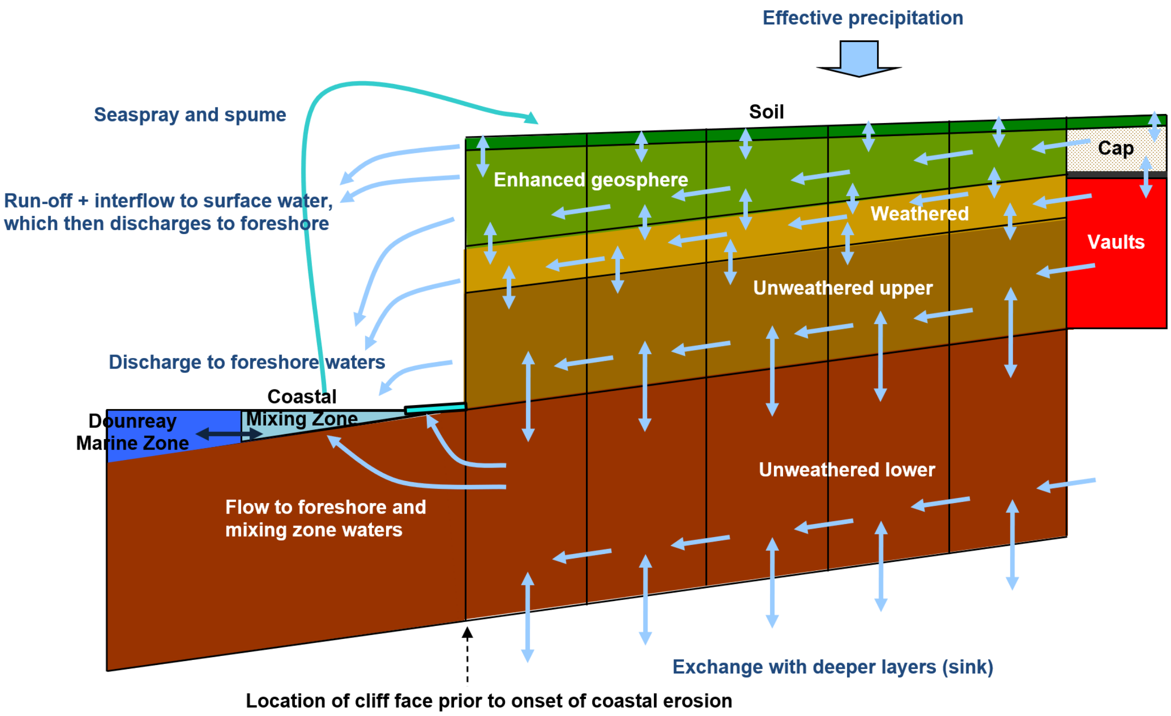

Figure 7.4: Schematic (not to scale) of the Run 5 geosphere conceptual model showing water flows (blue arrows) between compartments for the Undisturbed Performance scenario at the present day [48]. Cross-section runs from northwest (left) to southeast (right).

411 To allow for variation in the hydrogeology along the flow path, each geosphere compartment has its own individual flow specification (pale blue arrows in Figure 7.4). The flows are quantified by the local-scale hydrogeological model for the D3100 area [202]. There are small imbalances in the specified flows owing to the aggregation of results from the more detailed hydrogeological model into the PA model, and the PA model calculates an additional balancing flow to account for this:

- Water infiltrates the soil layer as hydrologically effective rainfall (HER) and recharges the enhanced geosphere layer, with excess water assumed to discharge to surface water as run-off (balancing flow).
- Water flows through the enhanced geosphere, some flowing downstream and some recharging the saturated weathered bedrock layer. Upward flow from the enhanced geosphere to the soil is specified, but the layer is designed to ensure that such upward flows, for example through periodic raising of the water table, do not occur or are very low. As for the soil layer, the balancing flow is excess water discharging to run-off as interflow.
- A proportion of the water flowing into the saturated weathered bedrock flows downstream, another proportion may flow upwards into the enhanced geosphere, a proportion may percolate to the deeper bedrock (upper saturated unweathered layer), and water may also flow upwards from the unweathered layer. The balance is provided through flow to and from the unweathered bedrock. At the cliff face, the horizontal flow component discharges to the foreshore.

- Flow from the near-field carrying radionuclides is assumed to mainly enter the geosphere in the upper unweathered saturated bedrock layer[28]. A proportion of the inflow entering this layer flows downstream, another proportion may flow upwards into the weathered saturated layer, and the balance is assumed to flow to or from the lower unweathered layer. Again, at the cliff face, the horizontal flow component discharges to the foreshore.
- The water flow logic for the lower unweathered saturated layer is similar to the upper unweathered saturated layer, with the exception that any water leaving the bottom of the compartment flows into a sink. At the cliff face, the horizontal flow from the lower unweathered saturated layer discharges to the foreshore and marine waters.

412 To represent retardation in the geosphere, the Run 5 PA considers two types of transport pathway with associated porosities and K_d values:

- Flow in the enhanced geosphere and weathered bedrock is assumed to be predominantly in weathered Devonian rock with a porous matrix.
- Flow in the unweathered Devonian bedrock is assumed to be mainly in fractures, and a fracture material has been defined to represent the transport properties of the fracture linings. A further material has been defined for bulk Devonian matrix with an enhanced porosity for simulation of matrix diffusion from the fractures (see conceptual model in Figure 6.19).

413 During coastal erosion, the soil, enhanced geosphere, weathered layer and upper unweathered layer of the geosphere between the facilities and the coast (Figure 7.4) are gradually eroded onto the foreshore and washed away by the sea. The erosion profile is assumed to remain similar over time (i.e. sea-level rise does not overtop the cliffs). After a time, likely to be tens of thousands of years in the future, the climate and sea levels are expected to stabilise and coastal erosion is assumed to cease. At some point much further in the future, a gradual cooling of the climate is expected. Eventually, sea level will start to fall in response to global build-up of ice volumes and new or emergent land will start to be exposed off the coastline at Dounreay. The emergence of new land was represented in earlier iterations of the D3100 project PA model when it was thought that land might start to emerge after around 50,000 years. However, based on updated projections of long-term climate change, glaciation and sea-level fall is not likely to affect Dounreay for over 100,000 years [153] (Section 6.3.4). This is well after the peak of calculated doses from D3100 has passed, and so sea-level fall and the emergence of land is no longer significant to the results of the D3100 project PA.

Marine environment

414 The Run 5 PA model for the marine environment is based on the compartment model developed specifically for Dounreay [292] and used in the Shaft PA [254] (Figure 7.5). Two additional zones are added in D3100 project PA to the model shown in

28 Near-field derived flow is apportioned between the weathered and unweathered upper bedrock layers based on their relative thicknesses.

Figure 7.5 to provide the interface between the geosphere and marine environments (see Figure 7.4). The foreshore receives material from cliff erosion, surface water discharging over the cliffs, and groundwater discharging through the cliffs. The foreshore is washed regularly by tides. Offshore is a narrow coastal zone that acts as a mixing interface between the shore and the Dounreay marine compartment shown in Figure 7.5. This mixing zone can maintain higher radionuclide concentrations than the larger Dounreay compartment and can contribute to elevated uptake of radionuclides in molluscs growing near the foreshore, and to elevated radionuclide concentrations in sea spray and spume transporting radioactivity from the sea back onto the soil above the cliffs.

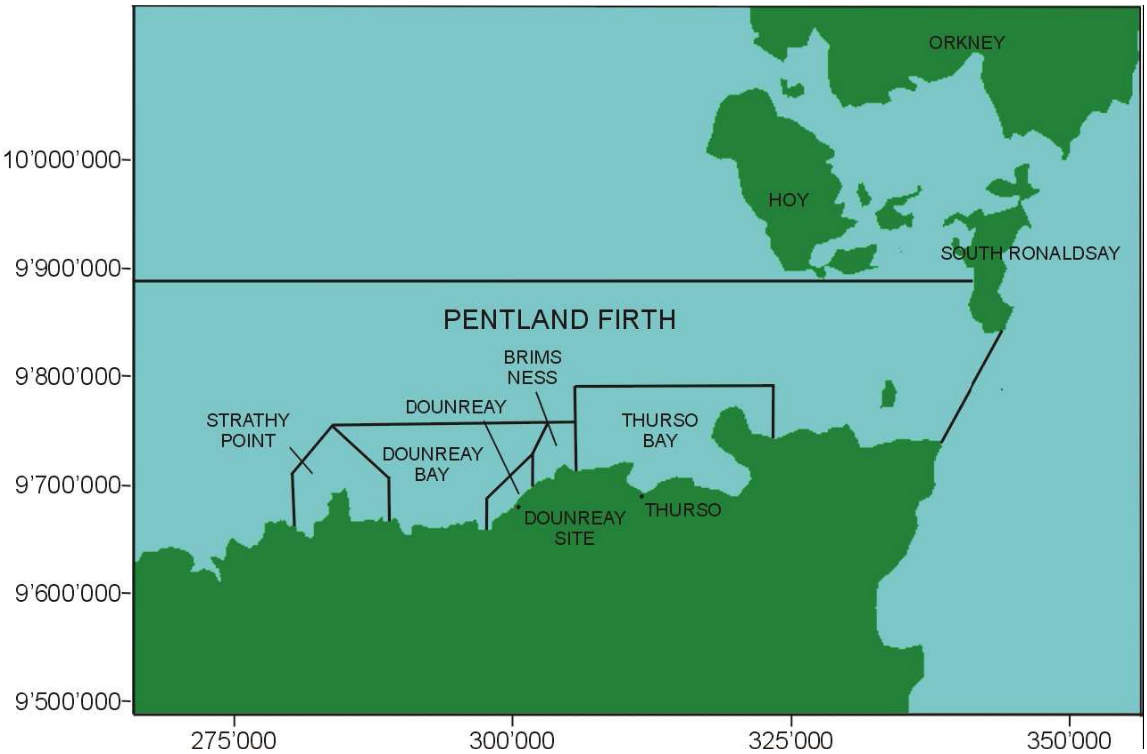

Figure 7.5: Compartments for the Run 5 PA marine model [292]. Waters beyond the Pentland Firth are considered as a single compartment (termed “Elsewhere” in the PA model).

7.5.3 Biosphere conceptual models

GRA 6.3.30	Consider different groups of people that could be at risk of exposure (potentially exposed groups) in order to identify a person representative of those people at greatest risk at a given time.
GRA 6.3.31(a)	Substantiate the choice of potentially exposed groups as being reasonable and suited to the particular circumstances. The location and characteristics of the groups considered should be based on the assessed releases of radioactivity and on assumptions about changing environmental conditions.
GRA 6.3.31(b)	The habits and behaviour assumed for people in potentially exposed groups should be based on present and past habits and behaviour that have been observed and that are judged relevant. Metabolic characteristics similar to those of present-day populations should be assumed.

GRA 6.3.31(c)	Other parameters (i.e. non-behavioural and metabolic) used to characterise a representative member of a potentially exposed group should be generic enough to give confidence that the assessment of risk will apply to a range of possible future populations.
GRA 6.4.9(b)	The investigation and characterisation of the biosphere should be sufficiently comprehensive to support calculations of dose during the period of authorisation and should be proportionate to the assumptions made in the environmental safety case for calculating risks after the period of authorisation.
GRA 7.3.14	Follow radiological protection advice generally accepted at the time of use for the assessment of dose and risk (e.g. dosimetric data and the applicable risk coefficient). Uncertainties in these areas are common to all radiological assessments and are normally left implicit. There is, therefore, no special reason to include them explicitly in assessments supporting the environmental safety case for a disposal system.

415 The model of the biosphere and the geosphere/biosphere interface is determined largely by considering how humans might be exposed to radioactivity released from the facilities. For information, the Run 5 PA calculates the doses/risks that could be received from a wide variety of possible uses of the water and land contaminated by releases from D3100 – termed exposure pathways. However, given that the land is only currently suitable for rough grazing, many of these pathways are not very likely. For comparison to the regulatory performance measures, it is necessary to define human behaviour on the basis of reasonable assumptions about habits and possible interaction with the exposure pathways.

Exposure pathways

416 The pathways considered for exposure of the potential RPs in the Run 5 Undisturbed Performance scenario are (Figure 7.6):

- External irradiation (from contaminated soil or sand and/or sea water).
- Ingestion of crops grown in contaminated soil (green vegetables, root vegetables, potatoes).
- Ingestion of animal products (beef and mutton as well as milk, eggs and poultry). Stock is assumed to be raised on contaminated pasture and to drink contaminated water from ditches.
- Ingestion of aquatic foods (sea fish, winkles, and crustaceans).
- Inadvertent ingestion of contaminated soil or sand.
- Inhalation of contaminated dust and marine aerosols.
- Skin contamination from foreshore sediment.
- Inhalation of radioactive gas.

417 Similar exposure pathways have been considered for the intruders in the inadvertent human intrusion Disturbed Performance scenarios, with the addition of water submersion considered for one of the RPs (Figure 7.6; see Section 7.5.5).

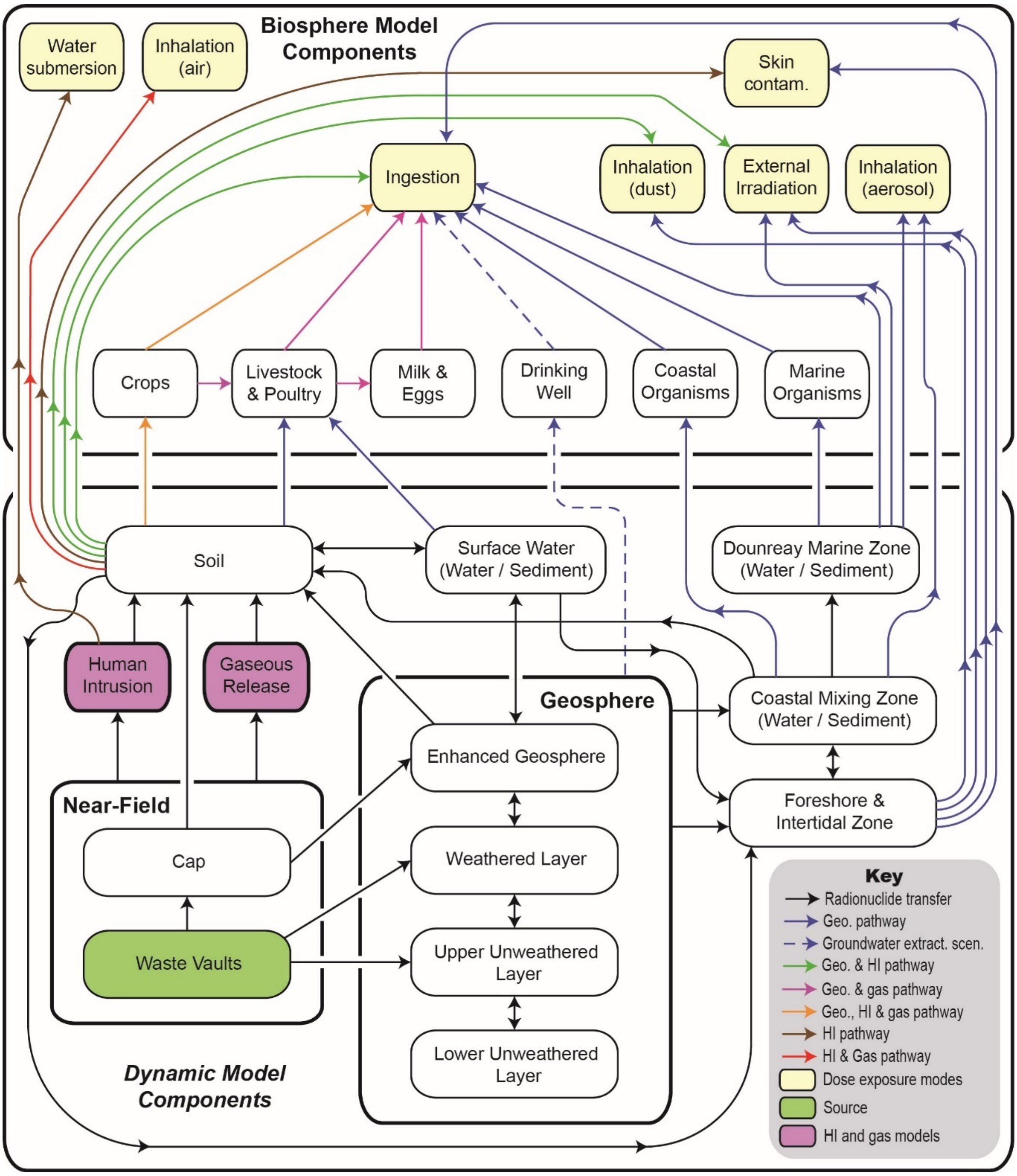

Figure 7.6: Human exposure pathways determined in the Run 5 PA biosphere model for both Undisturbed and Disturbed Performance.

418 Standard uptake and transfer factors and dose coefficients to calculate the impact from each Becquerel of radioactivity have been used where possible [48]. The committed effective dose has been calculated, rather than the dose to individual organs. The GRA [19] does not require calculations of absorbed or equivalent doses to individual organs and tissues, provided that the dose rates are sufficiently low that the thresholds for severe deterministic injury to individual body tissues are unlikely to be exceeded. As discussed in Section 7.7, all calculated impacts are below this level.

Definition of RPs for exposed groups

419 As required by the GRA [19], the Run 5 PA considers a performance measure of radiological dose to a range of potential RPs during the period of authorisation (i.e. while the facilities are under active control – Requirement R5). Following the end of the period of authorisation, the performance measure is radiological risk to potential RPs (i.e. PEGs – Requirement R6). The definition of these RPs and their associated exposed groups and parameterisation of their behaviour for the Run 5 PA are discussed in [48] and summarised below.

420 The methodology for the selection of RPs for the Run 5 PA is based on recommendations by the IAEA [293]. The RPs for the period of authorisation are based on observations of present-day activities in the Dounreay area, as described in the Dounreay habits surveys conducted for SEPA[29] [206; 207; 208; 209]. Only those habits that could currently lead to exposures from D3100 are included, and one potential RP making maximum use of each pathway is defined:

- Angler – An RP eating fish caught by line from the rocky foreshore. All of the fish consumed by this RP in a year are assumed to be caught in the sea directly offshore from the facilities.
- Potter – An RP eating crustaceans (lobsters and crabs) caught offshore by potting. Again, all of the crustaceans consumed by this RP in a year are assumed to be caught directly offshore from the facilities.
- Walker – An RP who regularly walks on the cliffs/foreshore, spending ca. 400 hours per year on the small strip of cliff and foreshore north of the facilities.
- Winkler – An RP collecting winkles from the foreshore downflow from the facilities.
- Livestock farmer – An RP raising beef cattle and sheep on the grass growing on the cap of D3100 and between the facilities and the coast. The annual consumption of beef and mutton for the RP is assumed to be entirely from livestock that have grazed only on contaminated grass – this is a pessimistic assumption as the livestock reared by a farming group will actually be grazed over a much larger area than can be contaminated by the facilities.

421 The RPs are assumed to use the area potentially contaminated by D3100 to the maximum plausible extent while undertaking their characteristic activities. They provide bounding potential doses for a single exposure pathway. The same RPs are assumed to persist beyond the period of authorisation in the Run 5 PA. Therefore, in terms of the results of the PA, there is a continuum of calculated impacts to these groups over time and all that changes is the GRA performance measure to which the

29 The Run 5 PA uses observation-weighted averages derived from the habits data from all four published surveys. This means each observation, independent of the year it was recorded, has been given the same weighting when deriving an average value. This was undertaken to avoid years with a single or small number of observations having an unduly large influence on the average, as would be the case if survey-weighted averaging (i.e. averaging the mean values of the four surveys) was used.

results are compared. The geosphere/biosphere interface and the interaction of the Run 5 RPs at the interface are illustrated in Figure 7.7.

422 Owing to uncertainties about how society and the climate will evolve in the long-term, the IAEA [293] recommends that, for timescales in excess of 10,000 years, assessment calculations should adopt a hypothetical critical group (i.e. RP) based on a breakdown of society and a widespread return to a subsistence lifestyle in a temperate climate. This approach for the long term is adopted in D3100 project PA to define a Crofter RP that experiences multiple exposure pathways from D3100 through the use of the contaminated area to support a subsistence lifestyle.

423 Consistent with the recommendations of the IAEA, extreme (i.e. unlikely) habits are avoided in the definition of the Crofter RP. Only reasonable behaviour is considered in order to define an RP that is suitable for decision-making. A self-sustaining crofting community could arise in the future on the coastal strip of agricultural land extending northeast from the facilities and southwest towards Sandside Bay. For the purposes of the Run 5 PA, such a community is assumed to consist of a collection of crofts, each of sufficient size to allow production of a range of foodstuffs. Bartering of produce between crofts would enable the community to be self-sustaining, with individual crofts focusing on the produce most easy to derive on the basis of their location and size.

424 For the Crofter RP, a croft is assumed to be situated on the site of D3100 using an area of about 4 ha of arable land for cultivation, and 4 ha for the stocking of cattle (see Figure 7.7 – this farm land is assumed to cover the cap and the geosphere furthest from the coast). A further 4 ha of land with poor soil is assumed for the grazing of sheep nearest the cliff-line. These areas of ‘farming’ and ‘grazing’ land are considered to be sufficient to support one croft and can be provided by the surface area of the cap over the facilities and the land between the facilities and the coast at the present day. However, loss of land by erosion in the future might mean that there is insufficient contaminated land to support a single croft. In such a situation, other adjacent land is assumed to be used to make up the difference; this land would not be directly contaminated by radionuclides released from the facilities, and is assumed to be uncontaminated.

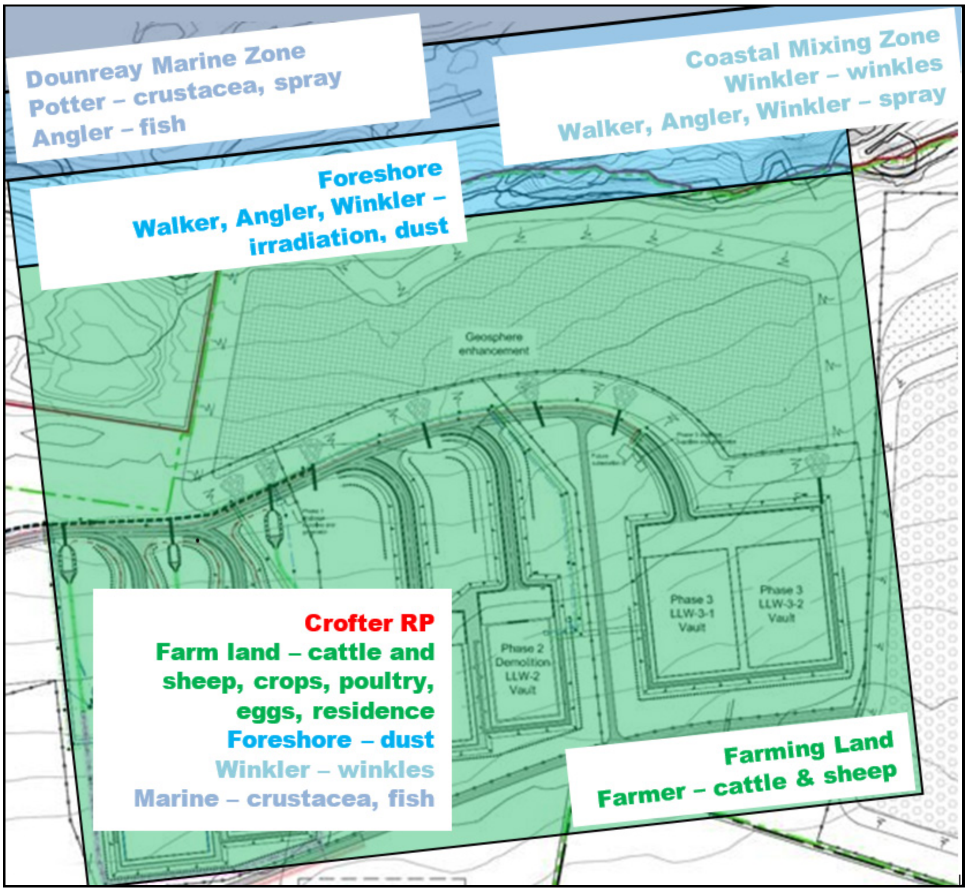

Figure 7.7: Illustration of the geosphere/biosphere interface in the Run 5 PA model and the interaction of the RPs with this interface. The figure is around 600 m across. The black lines and shaded boxes indicate the main near-field and geosphere PA flow model components underlying the biosphere. The foreshore, coastal mixing zone, and marine zone are common to the PA flow model and biosphere calculations.

425 While a wide range of foodstuffs is currently produced in various locations in Caithness, the strip of land between the D3100 and the cliffs is considered to be only suitable for the grazing of cattle and sheep (for which it was recently used periodically), and arable farming if the land were to be improved. The Crofter RP is defined as a family living in a house above D3100 and farming the land between the house and the cliff-line. The Crofter RP is assumed to derive all of its meat (beef, lamb, and chicken) and eggs from livestock raised on contaminated pasture and water, and is assumed to consume all of its required green and root vegetables from produce grown on contaminated arable land. The Crofter RP is also assumed to obtain fish, crustaceans and molluscs from the contaminated foreshore and marine waters offshore from the facilities. The family is assumed to consume meat and potatoes (the main contaminated foodstuffs) at the critical group rates given in the SEPA habits surveys [48, Tab.5.7] and the remainder of foodstuffs at the average UK rate [294]. Bartering activities by the crofting family will result in neighbouring crofters being exposed to contaminated foodstuffs derived from the site, but to a lesser degree than the Crofter RP. Foodstuffs that are unlikely to be derived from the contaminated area are assumed to be obtained by the Crofter RP through barter.

This results in the average adult of the Crofter RP deriving around one-third of its calorific intake from contaminated foods [48].

426 Defining RPs on the basis of a few highly-exposed individuals is consistent with regulatory guidance for assessment of radioactive discharges and comparison of a calculated actual dose to an observed critical group with a dose constraint (cf. Requirement R5) [295, ¶3.7.11]. However, it should be noted that this guidance is concerned with extant groups and compliance with a dose constraint, rather than hypothetical groups and comparison to a risk guidance level. Although the assumption that exposure occurs and the calculation of a conditional risk for a Crofter RP is bounding, it is more likely that the area contaminated by releases from D3100 might be used by several individuals as part of a crofting community[30]. The bounding approach to definition of the Crofter RP is cautious, and the Run 5 PA results for the Crofter RP can readily be used to demonstrate compliance for disposals of a specific inventory. However, for a more realistic indication of impacts and when using the Run 5 PA results to support analysis of disposal activity levels to meet the regulatory guidance, an alternative RP, the Crofting Community, is defined. This RP is based on a similar hypothetical construct to the Crofter RP, but calculates an estimate for actual risk, adopting a more realistic representation of the probability that a calculated dose will be received (the expectation value) rather than cautiously assuming this value is one.

427 For the Crofting Community RP, consideration is given to the probability that a member of a crofting community, similar to that described for the Crofter RP, would farm in the area contaminated by releases from D3100 compared to any other area for the same farming activity. This consideration is undertaken through calculation of an expectation value for the proportion of land required for an activity to support the entire community (e.g. grazing sheep, growing vegetables) that would involve the area contaminated by D3100.

428 The area that might be used by a hypothetical crofting community in the future is difficult to constrain. The Land Reform (Scotland) Act 2003 defines a crofting community body (CCB) as representing a crofting community [296], but the basis for formation of a CCB is not prescriptive as to the area involved. For the purposes of illustrating the actual risk, an area of 10 km^2 has been used based on the IAEA suggested area of a farming community in a reference biosphere for a safety assessment for deep waste disposal [297, §C.3.4.4]. This would equate to roughly 83 crofts based on the croft size of 12 ha discussed above for the Crofter RP.

429 Consideration is also given to the ability of the contaminated area to produce foodstuffs. The consumption rates for the community are calculated by assuming that each house is occupied by four individuals: two adults, a child and an infant. The consumption rates for the individual Crofter RP are used, and are scaled for the child and infant using the scaling factors given in [207]. For each foodstuff, the area needed to produce the amount consumed by a community is calculated. Due to the large total area required to produce all of the considered foodstuffs in comparison to

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30 In this context, it is interesting to note that before construction of D3100, there were three tenants with parts of their crofts / farms on the D3100 development site *(pers. comm. G Morgan e-mail to R. Houghton on 28 October 2019)*.

the size of the contaminated area, there is then a need to prioritise land use such that, if the contaminated area is insufficient to meet the need of every activity, the activities producing the foodstuffs with the greatest impacts are considered first. For land, the area is assumed to be sufficient to produce all eggs and poultry needs for the community. The area is then proportioned for raising sheep, beef and vegetables. For the marine foodstuffs, the area modelled as being contaminated by releases from D3100 (Dounreay Waters) is of sufficient area to support the entire community. Therefore, the assumption is that all of the marine foodstuffs used by the community are contaminated (expectation value of one).

430 The estimated actual risk, rather than the conditional risk used for the other RPs, is then calculated by multiplying the ingestion dose (assuming all of the foodstuff is contaminated), the expectation value for the proportion of the contaminated ground/water used to produce foodstuff (see below) and the probability given in the GRA [19, ¶6.3.14] that the dose will result in a serious health effect (dose to risk conversion factor of 0.06 Sv^{-1}). For irradiation and inhalation pathways, the calculation of risk to the Crofting Community RP is simplified by considering a total area used by an individual involved in a generic crofting activity (farming, fishing) and determining the expectation value for the proportion of the area that would be contaminated. The expectation value can then be multiplied with the dose from the activity if it was all undertaken in the contaminated area and the probability that the dose will result in a serious health effect to determine the risk.

Gas pathway

GRA 6.4.10(b)	Consider features and properties of the site related to release and transport of radionuclides in the gas phase.

431 Concretes and fractured rocks have permeabilities that are sufficiently high to allow gas to escape the vaults, and thus gas migration out of the vaults is possible. There are three radionuclides in the D3100 inventory that could give rise to potential releases of radioactive gas: ^{3}H incorporated in hydrogen from anaerobic corrosion of metal; ^{14}C incorporated in methane from anaerobic degradation of materials; and ^{226}Ra decaying to give ^{222}Rn.

432 Results from the Run 3 and 4 PAs [278; 279] show that the calculated dose from inhalation of ^{3}H gas drops off rapidly with time, primarily as a result of its short half-life (12.3 years). To calculate a dose in these assessments, three conservative assumptions were made: immediate saturation and the start of corrosion, unimpeded release of the hydrogen gas, and immediate occupation of a house on the cap. For Run 5, the calculation of exposure to ^{3}H gas is not considered as these cautious assumptions do not align with the expected future evolution of the site. This judgement is based on four qualitative arguments:

- There will be a period of control for the adjacent Dounreay site while intermediate-level wastes continue to be stored there until a final management solution is implemented [298]. Therefore, it is reasonable to assume that controls on building a house on the cap of D3100 adjacent to the Dounreay site will be in place for some decades after closure. Also, plans for the Dounreay site end-state foresee a possible period of control of

150 years to allow residual contamination to decay to "no danger" levels [298].

- Although decisions have yet to be taken, there will almost certainly be a period of monitoring and control after closure of D3100.
- The 2011 ESC for LLWR did not consider release of ^{3}H gas after closure for the same reasons as indicated above – closure of the LLWR is not expected for 100 years, after which ^{3}H will have decayed to very low levels [299]. The assessment for LLWR did consider release of ^{3}H during the period of control, but through the evapotranspiration of tritiated water vapour rather than as hydrogen gas [300]. For tritiated water vapour to occur at D3100, the ^{3}H in the wastes would first have to be released and migrate to the surface. However, the resaturation of the D3100 vaults and the release of radioactivity to groundwater will take at least 100 years [181]. By this time, the amount of ^{3}H in the wastes, and thus the annual dose, will have dropped to very low levels.
- Corrosion and hydrogen gas generation can occur while the wastes remain unsaturated, but the gas will react with the waste and water, reducing phases such as iron(III) oxides and organic compounds, rather than migrating to the surface through the cap [301]. Despite resulting from the same gas generation processes of metal corrosion and anaerobic degradation foreseen at D3100, landfill gas is generally composed of CO_2 and CH_4 with only trace amounts of hydrogen [302, Tab.6.1]. Monitoring of gas compositions in the trench wastes at LLWR has not detected hydrogen above around 0.5% by volume [300].

433 As part of Run 5 PA development, the D3100 PA ^{14}C gas conceptual model was enhanced [48, §5.8] based primarily on the gas modelling work undertaken for LLWR [303; 304; 305]. In the Run 5 PA, ^{14}C gas generation is considered for four material groups for which the ^{14}C inventory is apportioned based on weight percentage in the inventory:

- Cellulose and Plastics/Rubbers: CO_2 and CH_4 are produced through anaerobic degradation of organic material. It is cautiously assumed that 50% of the ^{14}C inventory within cellulose and plastics/rubbers is released as CH_4 to the atmosphere. The other 50% is released as CO_2 that forms carbonate within the vaults.
- Metals: For metal degradation, it is assumed that 100% of the ^{14}C inventory is released as CH_4 to the atmosphere, following the approach used for LLWR [305, §5.3.3].
- Other Materials: A significant proportion of the D3100 2020 inventory is associated with "other materials". As this group contains a wide array of materials with greatly differing properties, the most cautious assumptions from the cellulose, plastics/rubbers, and metals material groups are used.

434 The Run 5 PA calculates potential doses from ^{14}C gas to the Crofter RP assuming that the house and associated garden are built on the vault cap to intercept gas releases. Exposure pathways to the RP are inhalation of ^{14}C gas within the house

and consumption of foodstuffs contaminated by ^{14}C gas releases. Crofter RP consumption rates of contaminated food are cautiously assumed to be the same as for the groundwater pathway (even though the land area is much smaller). No account is taken of any gas dispersion processes during migration from the vaults. The pathways considered are summarised in Figure 7.8.

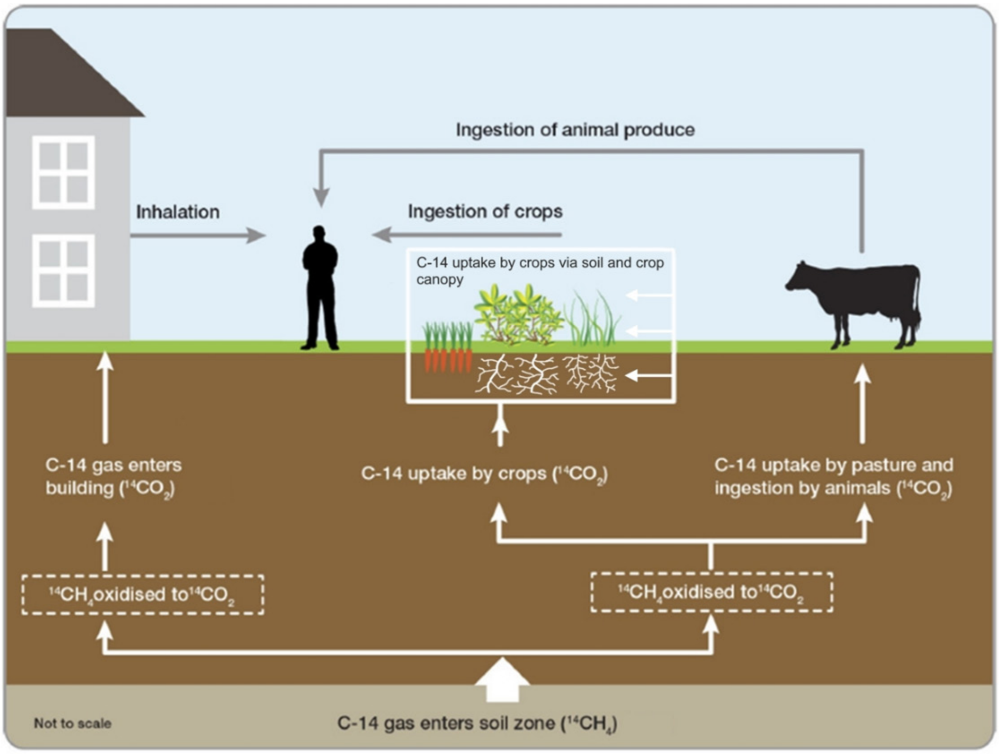


Figure 7.8: ^{14}C pathways to the Crofter RP in the Run 5 PA. Modified from Figure 6-3 in [305].

435 The Run 3 and 4 PAs considered two release mechanisms of ^{222}Rn gas:

- Radon released directly from the waste, through *in situ* ^{226}Ra decay, that seeps from the vaults to the surface.
- Decay of ^{226}Ra related to releases from the vaults to groundwater generating radon that is released from contaminated soil downstream of D3100.

436 For the Run 5 PA [48], it is considered that the first of these, direct release of radon through the cap, is not feasible. Removal of the direct ^{222}Rn release pathway is justified through a more realistic consideration of the effective diffusion coefficient of radon when considered with the expected conditions at closure of D3100. Saturation of the ground between the waste and the surface (Figure 6.17) along with the fact that the cap is likely to include a layer of fine-gained material such as clay mean that the chance of direct ^{222}Rn release through diffusion is not possible owing to its short half-life (3.8 days) [48, §5.8.1]. The second release mechanism, exposure to ^{222}Rn generated from ^{226}Ra in soil, is considered in Run 5 and assumes no attenuation by covering material.

437 It is important to note that the RPs for the gas pathway and for the groundwater pathway might be the same if the timings of the calculated doses are the same. Both are to occupants of the contaminated ground above and/or downstream of the D3100

vaults – the Crofter and Crofting Community RPs. The potential for addition of the calculated impacts from each pathway should be considered when viewing the results.

7.5.4 Disturbed performance

438 The stylised scenarios defined for the Run 5 PA to assess the possible consequences of inadvertent human intrusion assume exposure to waste from D3100 exhumed or uncovered by a variety of means (e.g. borehole, quarry – Section 7.4.3) [48]. For each exposure pathway, the waste activity is modified according to the total volume of material into which the waste is mixed during its extraction. However, otherwise the only reduction in activity in D3100 that is considered in the inadvertent human intrusion is by radioactive decay (i.e. leaching by groundwater is not modelled). For this reason, the inadvertent human intrusion calculations become more unrealistic over time and thus highly pessimistic at times more than 10,000 years after closure. The Run 5 PA model considers several RPs (Table 7.2) across the scenarios, with the results being displayed for each RP in the same output for comparison [48].

Table 7.2: Summary of Human Intrusion RPs and their exposure pathways considered in the Run 5 PA.

Scenario	RP	Exposure pathways
Borehole	Worker	Skin contamination, ingestion of contaminated material, inhalation of contaminated material and external irradiation.
	Truck Driver	Skin contamination, ingestion of contaminated material, inhalation of contaminated material and external irradiation.
	Resident	Ingestion of contaminated material, ingestion of contaminated crops, inhalation of contaminated material, inhalation of radon gas (from Ra-226) and external irradiation.
Quarry	Worker	Skin contamination, ingestion of contaminated material, inhalation of contaminated material and external irradiation.
	Truck Driver	Skin contamination, ingestion of contaminated material, inhalation of contaminated material and external irradiation.
	Resident	Ingestion of contaminated material, ingestion of contaminated crops, inhalation of contained material, inhalation of radon gas (from Ra-226) and external irradiation.
Controlled Intrusion	Controlled Intruder	Skin contamination, ingestion of contaminated material, inhalation of contaminated material and external irradiation.

Scenario	RP	Exposure pathways
Uncontrolled Intrusion	Uncontrolled Intruder	Skin contamination, ingestion of contaminated material, inhalation of contaminated material, external irradiation, external irradiation from wet clothing.

439 For the other Disturbed Performance scenarios, all of the calculations are implemented through changes in parameter values to the Undisturbed Performance PA models (Sections 7.5.1 to 7.5.3). The same RPs as in the Undisturbed Performance scenario are used.

7.5.5 Derivation of modelling parameter values

440 To support parameter value development, the Dounreay 2020 inventory (Table 4.3) has been screened to identify the subset of radionuclides that are potentially important to long-term performance of the disposal system and that need to be considered in the PA calculations [48, App.B]. This screening was also undertaken for previous iterations of the PA. For Run 5, an added factor was modelling of all of the radionuclides to be included in the SoF calculations. The screening is described further in Section 8.3.1 and resulted in 51 radionuclides being modelled in the Run 5 PA.

441 The parameter database for the Run 5 PA is formally documented in [48, App.C], providing an audit trail back to the source of the data supporting the derivation of parameter values. The Run 5 PA uses a mixture of site-specific and generic data, favouring the former where it is available. Where possible, minimum, maximum and best estimate parameter values are provided to support uncertainty analyses. Most of the data sources are either literature from international programmes, such as those organised by the IAEA (e.g. [306; 307]), or reports prepared to support this ESC, including the inventory report [47], the site characteristics summary [50], and the Run 1 PA common source database [177; 190; 191]. Characterisation of the diet and behaviour of the RPs is derived from the SEPA habits surveys [206; 207; 208; 209], the Run 1 biosphere database [191], and generalised habits data for radiological assessments in the UK [294].

7.6 Run 5 PA Calculational Tools

442 The Run 5 PA mostly uses the GoldSim-RT modelling tool [308; 309] to implement the PA conceptual models. GoldSim-RT was recommended for conducting radioactive waste disposal assessments in a review of software tools conducted on behalf of the Environment Agency of England and Wales [310]. GoldSim-RT is used internationally, and is maintained by a company (GoldSim Technology Group LLC) to ensure the software is quality assured for the conduct of assessments of radioactive waste disposal facilities.

443 GoldSim-RT provides specialised elements for representing contaminant and radionuclide species, transport media, transport pathways, contaminant sources, and receptors, and the coupled sets of differential equations underlying these systems. By linking the specialised elements together and integrating them with GoldSim's basic elements, contaminant transport simulations can be undertaken. The

mathematical equations used in the Run 5 PA are provided in [279] and [278], and the implementation of the Run 5 PA groundwater pathway models in the GoldSim-RT software has been verified using checking routines [279, App.1; 278, App.2; 48, App.A].

444 The Run 5 PA calculations for inadvertent human intrusion are undertaken in a GoldSim-RT tool [311] separate to that used to model the groundwater pathway. As noted earlier, in the inadvertent human intrusion modelling tool, the evolution of the waste concentrations over time in the D3100 vaults before intrusion considers decay only, and leaching by groundwater is conservatively ignored.

445 The Run 5 PA calculations for the gas pathway are implemented in a Microsoft Excel spreadsheet rather than using GoldSim-RT. However, the spreadsheet calculations are undertaken for particular times in D3100 evolution and the relevant radionuclide concentrations at these times are taken from the groundwater pathway GoldSim-RT model.

7.7 Run 5 PA Results

446 Three important considerations need to be taken into account when viewing the PA results presented here:

- First, the PA results are devised to illustrate potential consequences to aid understanding and demonstrate safety. PA results do not represent reality - rather they represent the consequences of a set of modelling assumptions. Simplifying assumptions made for the Run 5 PA are generally cautious, thereby increasing calculated consequences. Related to this consideration is the observation that any sharp changes in the pattern of PA results are likely to reflect changes in PA assumptions or model conditions (modelling artefacts), rather than real effects that might be observed.

- Second, many of the PA results presented in the following figures are plotted on logarithmic y-axis scales to show differences between sets of calculations. However, this means that small, and often insignificant, changes can look big on the figures. For example, on figures showing calculated radiological annual risk, a scale from 1E-03 y^{-1} to 1E-10 y^{-1} is used in this ESC, covering seven orders of magnitude (e.g. Figure 7.9a). This allows the figure to show the UK average annual risk from naturally occurring radioactivity (dose of 2.6 mSv y^{-1} converted to risk in Figure 7.9 – turquoise line; similar to background dose received in the Highlands [312]) and the regulatory risk guidance level (1E-06 y^{-1} [19]), and the PA results separated over a wide space on the figure. However, if the same results are shown with a linear y-axis scale (Figure 7.9b), the risk guidance level virtually coincides with the x-axis if the UK average dose is plotted, and differences between the PA results are not distinguishable. Providing the calculated risks from the D3100 remain consistent with the regulatory guidance level, they will not noticeably affect the actual annual radiological risk received by any individual (see also Figure 9.3).

- Third, the Run 5 PA results are calculated for adults. For information, calculation of doses to children (assumed age of 10 years) and infants (assumed age of 1 year) were undertaken in the Run 3 PA [278], and were only slightly higher than those to adults. The use of dose coefficients for a particular age, as provided in the international Basic Safety Standards [78], yields results that are valid only for a single instance in the exposed lifetime of an individual. Given the findings of the Run 3 PA, the low calculated risks to adults (see Sections 7.7.1 and 7.7.2), and the uncertainty over the applicability of the dose coefficients, together with the consideration that adults are most representative of the average of each of the exposed groups considered in the D3100 project PA, only the results for adults have been calculated in the Run 5 PA.

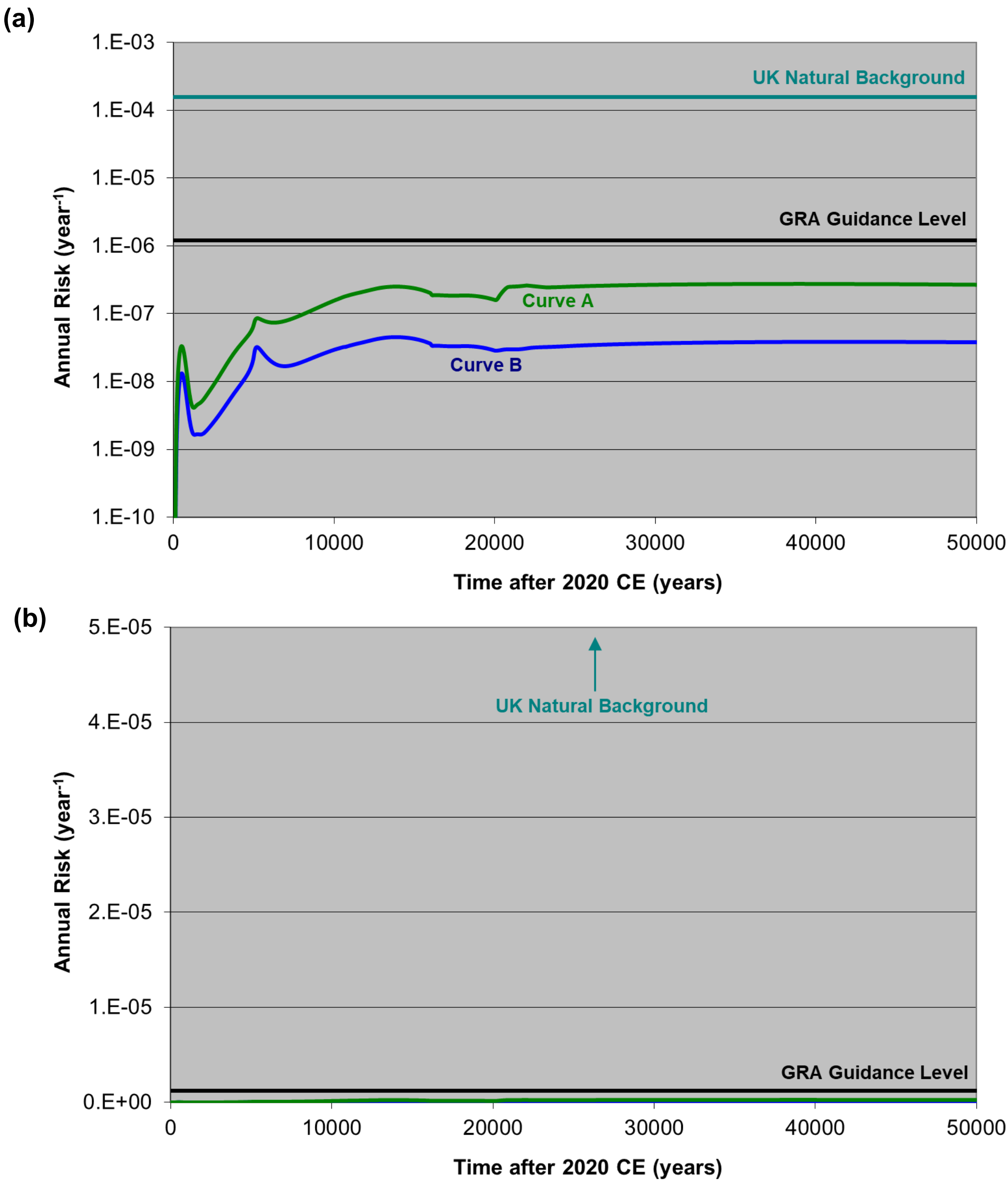


Figure 7.9: Two plots of the same data, showing two hypothetical curves of calculated annual risk against time. Figure (a) has a logarithmic y axis scale and Figure (b) a linear y-axis scale. The remaining figures of PA results in this ESC use a logarithmic scale to emphasise differences in results. However, as this figure illustrates, the differences are extremely small in terms of the annual dose received by any individual.

7.7.1 Radiological impacts during the period of authorisation

GRA 6.3.1	**Requirement R5: Dose constraints during the period of authorisation.** During the period of authorisation, the effective dose from the facility to a representative member of the critical group should not exceed a source-related dose constraint and a site-related dose constraint.
GRA 6.3.2	The following are the maximum doses to individuals which may result from a defined source, for use at the planning stage in radiation protection: − 0.3 mSv per year from any source from which radioactive discharges are made; or − 0.5 mSv per year from the discharges from any single site.
GRA 6.3.3	For the operational and active institutional control phases, consider HPA recommendations that a dose constraint of 0.15 mSv (annual dose) should apply to exposure to the public from a new disposal facility for radioactive waste.
GRA 6.3.4	For comparison with the source-related dose constraint, the assessment of effective dose should take into account both direct radiation from the facility and radiation from current discharges from the facility. For comparison with the site-related dose constraint, the assessment of effective dose should take into account radiation from current discharges from the facility, together with radiation from current discharges from any other sources at the same site (i.e. sources with contiguous boundaries at a single location).

447 For the purposes of the calculation of radiological impacts, the period of authorisation can be divided into two phases, the operational phase and the phase of active institutional control after closure during which access is controlled and the facilities are monitored. No assumptions about the date of closure or the nature or duration of institutional control after closure of the facilities are made in the calculations reported here. Access to all areas and farming on and around the facilities are assumed to be allowed immediately on closure. Therefore, all calculated impacts reported in Section 7.7.2 are presented as impacts following the period of authorisation. By meeting the regulatory performance measures for that period, the source-related dose constraint during the period of authorisation is also met. This leaves impacts during operations and performance against the site-related dose constraint to be considered here.

448 No routine releases of radioactivity to groundwater from D3100 are anticipated during operations. LLW will be conditioned and packaged before transport to the disposal vaults. Releases from the grouting facility are covered under the EASR 18 Permit for the Dounreay licensed site (where the plant is located) and are not considered in this ESC. Therefore, the only pathway for exposure of the public during routine operation of D3100 is through skyshine (i.e. radiation from the sky arising from interactions of gamma rays and x-rays (photons) emitted upwards from the vaults with air molecules). Calculations of doses to the public from skyshine have been undertaken separately from the Run 5 PA and are reported in Section 7.8. In all cases, calculated skyshine doses are greatly below the source related dose constraint of 0.3 mSv y^{-1} (and the 0.15 mSv y^{-1} constraint suggested by HPA), and this will be the case even if all of the vaults are open at the same time.

449 In addition to D3100, the other main sources of potential doses at Dounreay during the period of authorisation are discharges from the licensed site during operations and any contamination left following remediation of the licensed site. The total annual radiation dose from all sources at Dounreay was estimated to be 0.035 mSv for 2018 [313]. The maximum annual dose at the nearest houses related to external radiation from the site is 5 x 10^{-3} mSv y^{-1}, although the measurements probably just reflect natural variations in background radiation [314]. In combination with the calculated impacts from D3100, these doses are well below the GRA site-related dose constraint of 0.5 mSv y^{-1}. The end-state for the licensed site will be managed such that doses are below the GRA source constraint of 0.3 mSv y^{-1}. Further, terrestrial contamination associated with the licensed site end-state will not be in the same place as any contamination associated with D3100. Therefore, the exposure pathways for the two sources may not overlap.

7.7.2 Radiological impacts after the period of authorisation

GRA 6.3.10	**Requirement R6: Risk guidance level after the period of authorisation.** 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 (i.e. 1 in a million per year).
GRA 6.3.13	Radiological risk associated with a potential exposure situation corresponds to the product of the estimated effective dose that could be received, the estimated probability that this dose will be received and the estimated probability that detriment would occur as a consequence to the person exposed. For comparison with the risk guidance level, assessed risks must be summed over all situations that could give rise to exposure of the same person to radiation.
GRA 6.3.35	If there is a significant discrepancy between the results of a risk assessment and the risk guidance level, or if the probability distribution of dose at some future time is of concern, additional information should be provided to demonstrate that an appropriate level of environmental safety is assured.
GRA 6.3.14	For situations in which only stochastic effects of radiation exposure need to be considered (i.e. when the estimated annual effective dose is less than 100 mSv and the estimated equivalent dose to each tissue is below the relevant threshold for deterministic effects), a risk coefficient of 0.06 per Sv should be used.
GRA 6.3.16	If the estimated effective dose received over the period of a year or less is greater than 100 mSv it should not be combined with the probability of receiving the dose to give an estimated risk but the dose and probability should be presented separately.
GRA 6.3.19	Demonstrate that the measure chosen for comparison with the risk guidance level is reasonable (e.g. expectation (mean) value of risk) and present information about the sensitivity of the chosen measure to important parameter values.

GRA 6.3.22	In cases where the hazard presented by the waste warrants a detailed assessment of risks, present a probability distribution of dose covering the range of possible doses that a person representative of each potentially exposed group may receive and will provide the probability that this person receives any given dose. The probability distribution will vary with time into the future.
GRA 6.3.32	If two or more separate disposal facilities present significant risks to the same potentially exposed groups, consideration should be given to the combined risks.
GRA 7.2.8(b)	Show how radionuclides might be expected to move from the wastes through the immediate physical and chemical environment of the disposal facility and through the surrounding geological formations into and through the environment.

Undisturbed performance

450 After the period of authorisation ceases, the performance measure for post-closure safety is taken from the GRA [19, ¶6.3.10] as a risk guidance level to the RP at highest risk of 10^{-6} y^{-1}. As noted in Section 7.5.3, most of the RPs are considered on a conditional basis, conservatively assuming a probability of the exposure occurring is one. However, for the Community Crofter RP, an expectation factor is derived considering the probability of exposure.

451 For the reference Undisturbed Performance scenario in the Run 5 PA, none of the calculated risks are in excess of the risk guidance level over the timescale of the assessment. Peak risks occur after tens of thousands of years, but risks are falling beyond 100,000 years when the PA calculations are terminated. As might be expected, the most exposed RP is the Crofter (Figure 7.10). Figure 7.10 only includes the calculated impacts from all of the LLW and Demolition LLW vaults expected at D3100; no other authorised disposal facilities are likely to be present to add to these impacts by contaminating the same area of ground after the Dounreay site has been decommissioned [19, ¶6.3.32].

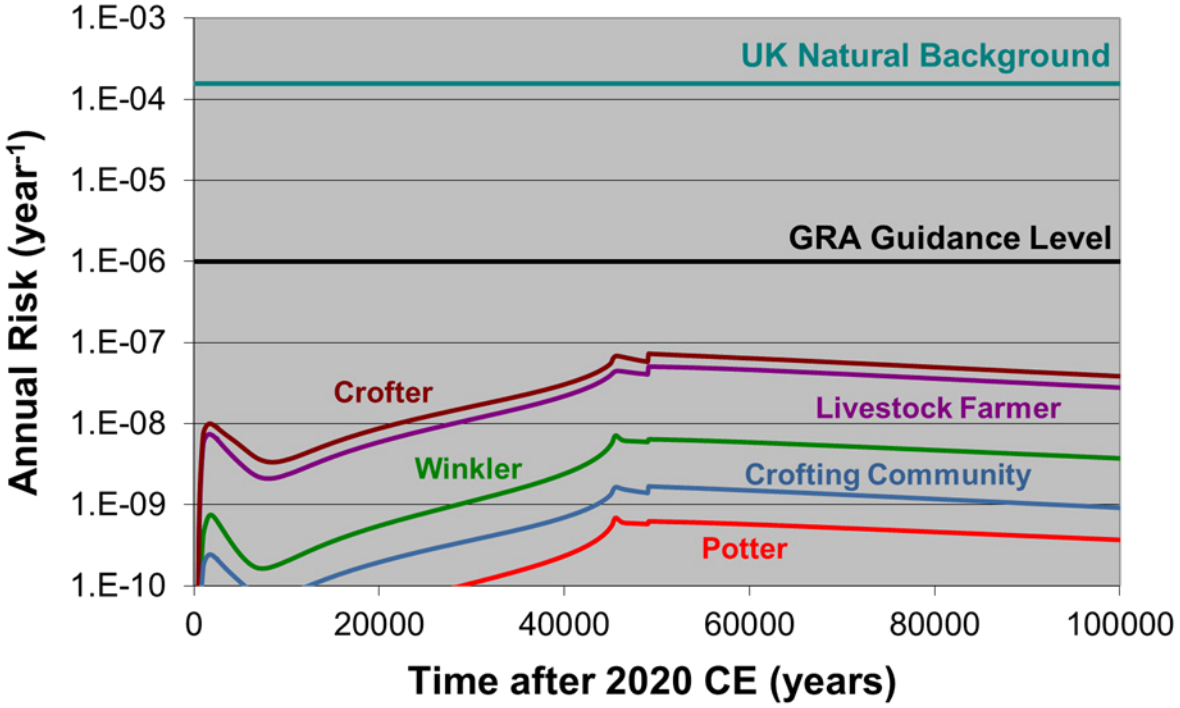


Figure 7.10: Calculated annual risks to RPs for the Undisturbed Performance scenario reference calculation [48]. Calculated risks to the Walker and Angler RPs are below 1E-10 y^{-1} (i.e. off the bottom of the figure).

452 The engineering of D3100 clearly limits the release of radionuclides and consequent exposure. Only after a few thousand years, by which time most of the radioactivity disposed of will have decayed, do calculated doses start to rise. This is related to the release of long-lived actinides once the engineering has degraded significantly; the release pattern of these actinides is delayed and spread out over time by the combination of a low-permeability wasteform and the alkaline environment provided by the conditioning cement grout. The sharp peak and gradual decline in risk seen after around 45,000 to 50,000 years relates to the modelled end of cement degradation and the release of uranium once alkaline conditions disappear.

453 The significance of each exposure pathway is illustrated by the breakdown of the dose to the Crofter RP (which sees all of the most significant exposure pathways in the model). The contribution of each exposure pathway to the annual dose to the Crofter RP is shown in Figure 7.11. A key exposure pathway is through livestock raised on the contaminated grazing and water between the facilities and the sea. The only other RPs that use this pathway are the Livestock Farmer and the Crofter Community. The dominance of the livestock pathway over all of the other pathways means that the Livestock Farmer RP shows an almost identical annual risk profile to the Crofter RP in Figure 7.10. The reason why the calculated Livestock Farmer RP annual risks are slightly lower than Crofter RP risks is that the Livestock Farmer is assumed not to consume contaminated poultry and eggs, fish and vegetables, and is assumed not to live on contaminated ground and, therefore, receive a dose from external irradiation.

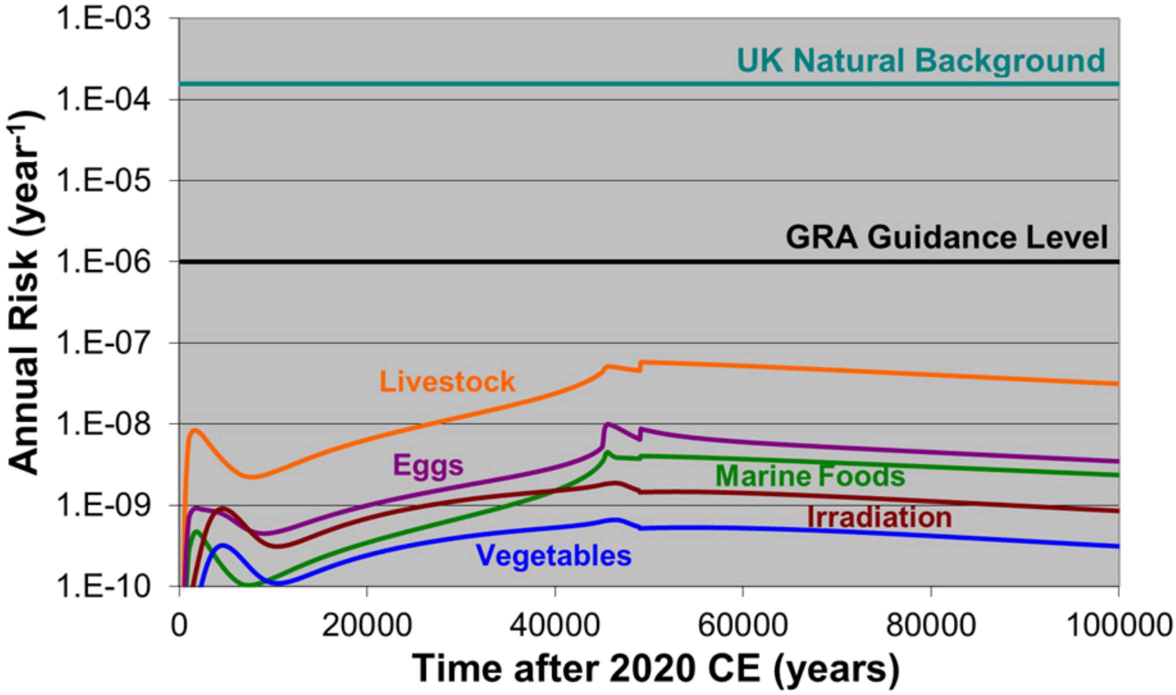


Figure 7.11: Exposure pathways for the Crofter RP for the Undisturbed Performance scenario reference calculation [48].

454 Only very low radionuclide concentrations are calculated in the coastal and marine waters, owing to the large diluting effect of the marine environment. As a result, marine fish and crustacea in the deeper waters also exhibit low calculated radionuclide concentrations. The low significance of consumption of marine fish and crustacea as exposure routes is illustrated by the very low annual risks calculated for the Potter RP (Figure 7.10).

455 Compared to the marine environment offshore, slightly higher radionuclide concentrations are calculated at the foreshore and in the intertidal area where eroded cliff material and discharging waters can reside for a time before being washed into the sea. Winkles (molluscs) are assumed to be collected from this area, and it is the consumption of winkles, rather than fish and crustacea, that dominate the marine foods pathway to the Crofter RP in Figure 7.11. The Winkler RP is assumed to consume an amount of molluscs equivalent to the high consumer behaviour in the SEPA surveys and, therefore, the Winkler RP in Figure 7.10 shows higher calculated risks but with a similar profile to the risks to the Crofter RP from marine foodstuffs in Figure 7.11.

456 The profiles of calculated annual doses for the Angler and Walker RPs reflect a dominant pathway of external irradiation while occupying the foreshore (as opposed to the main external irradiation pathway to the Crofter RP from contaminated soil). Calculated doses to these RPs are too low to feature on Figure 7.10. After 50,000 years, when sea levels stop rising and coastal erosion is assumed to cease, the calculated annual doses for the Angler and Walker RPs drop even further as contaminated material is no longer deposited by erosion on the foreshore and the calculated external irradiation dose falls.

457 The main radionuclides contributing to the dose to the Crofter RP are ^{226}Ra and daughters (^{210}Pb and ^{210}Po) as a result of decay of ^{234}U migrating from the facilities over long timescales and accumulating in the geosphere (Figure 7.12). The sharp peak and gradual decline in risk associated with uranium isotopes at around 45,000 years in Figure 7.12 relates to the modelled end of cement degradation, which results in a significant drop in near-field sorption of uranium The same radionuclides were the main contributors to calculated dose in the previous iterations of the D3100 PA.

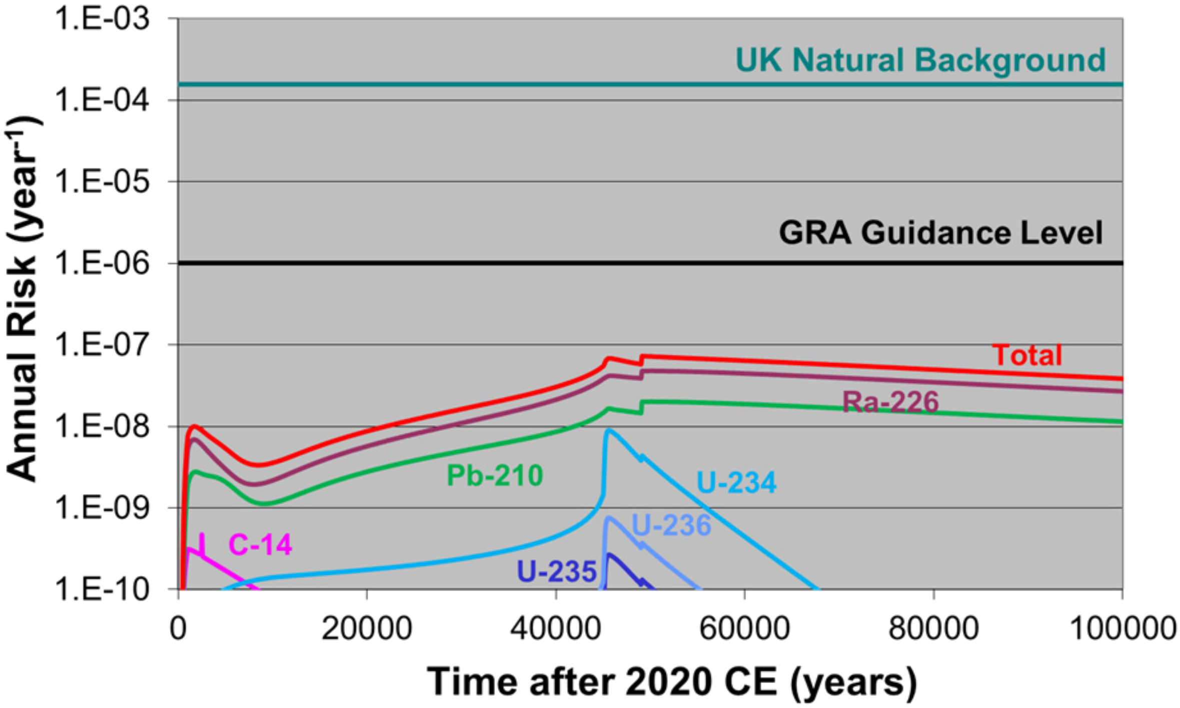


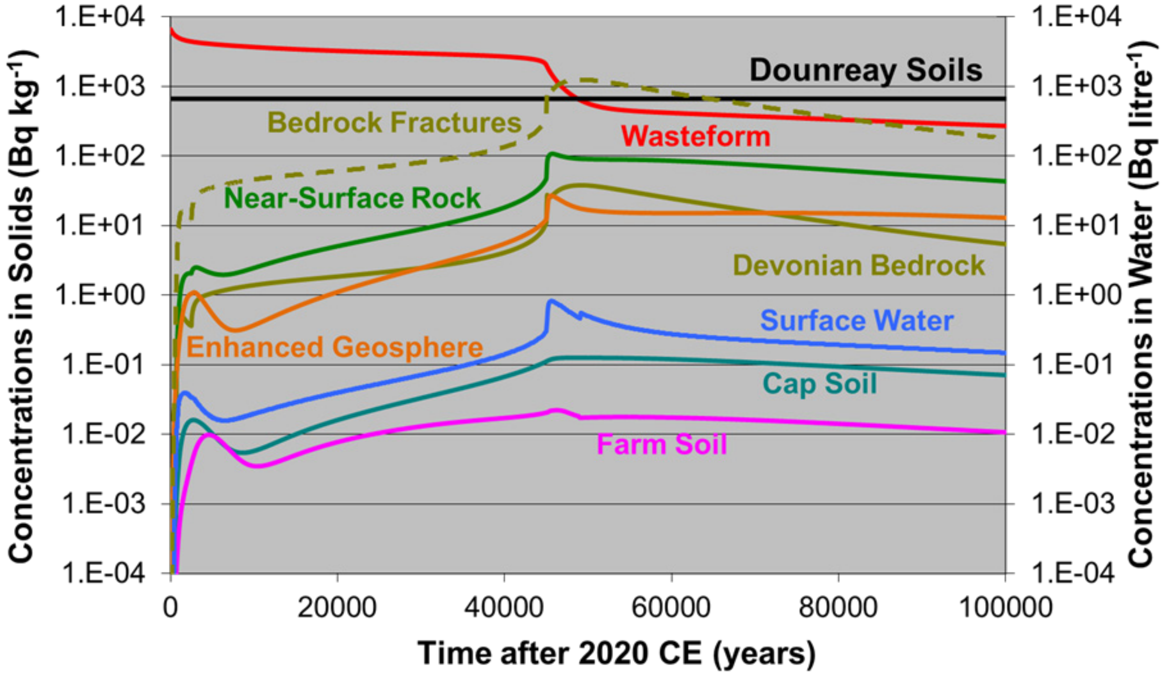
Figure 7.12: Contribution to the calculated total annual risk to the Crofter RP from individual radionuclides [48].

458 Figure 7.13 shows calculated average concentrations of activity in the environment, divided into total alpha and beta/gamma activity. Concentrations in Devonian bedrock and soils do not approach the present-day background concentrations in Dounreay soils (Table 6.10; [196]). Dilution means that only very low radionuclide concentrations are calculated for the marine environment. There is a steep initial fall in beta/gamma activity in the wastes through decay of short-lived activity and leaching of poorly-retarded radionuclides. The average wasteform concentration drops below present-day values in soils after ca. 150 years for beta/gamma activity. There is also a sharp initial fall in the alpha activity of the wastes, but after 150 years, the average wasteform concentration alpha activity is still about 4.5 times that of background and thereafter it drops very slowly as the activity is held in the vaults.

459 Note that the concentrations calculated for the Devonian bedrock in Figure 7.13 are averaged over the entire rock volume. However, radioactivity within the unweathered bedrock is likely to be concentrated in fractures and their associated surrounding diffusive zones. To account for this, “bedrock fractures” in Figure 7.13 denotes the concentrations when it is assumed radionuclides are limited to fracture zones.

Concentrations in the unweathered bedrock fracture zones reach up to values that are relatively similar to the background concentrations in Dounreay soils

(a)



(b)

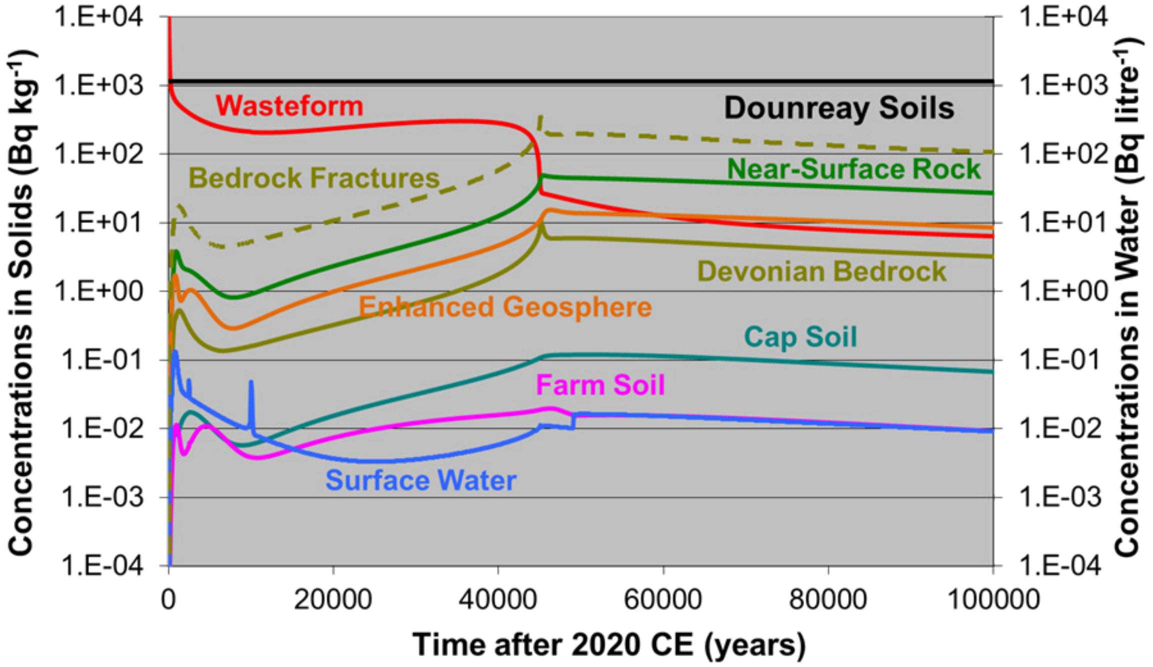


Figure 7.13: Total radionuclide concentrations (solids – Bq/kg; water – Bq/litre) in the main Run 5 PA media: (a) = alpha radioactivity; (b) = beta/gamma radioactivity [48]. Average background concentrations in soils from the D3100 study area (alpha activity = 667 Bq kg^{-1} and beta/gamma activity = 1150 Bq kg^{-1}) are also shown for comparison.

460 Figure 7.14 shows the calculated annual fluxes of total beta/gamma activity and total alpha activity leaving the facilities and entering the geosphere. The fluxes are orders

of magnitude less than the 2018 authorised annual liquid discharges from Dounreay [45], although it is recognised that the discharges are into different locations. They are also similar to natural groundwater fluxes of U-chain activity and ^{40}K calculated for a groundwater flow volume of 70,000 m^3 y^{-1} [315] (compared to a smaller flow of around 10,000 m^3 y^{-1} for the D3100 vaults rock volume). The peaks in discharges are related to changes in near-field retardation. The spike in beta/gamma discharges to surface waters at 10,000 years is related to an assumed change to oxidising conditions in the near-field leading to a sharp reduction in the calculated retardation of technetium at this time. Similarly, the increase in both beta/gamma and alpha activity discharges towards 45,000 years is related to a decrease in the calculated retardation of uranium and radium in the near-field. This increase in the release of radium, shown in the discharges of alpha activity, is then mirrored in the calculated release of its daughter, ^{210}Pb, in the beta/gamma discharges.

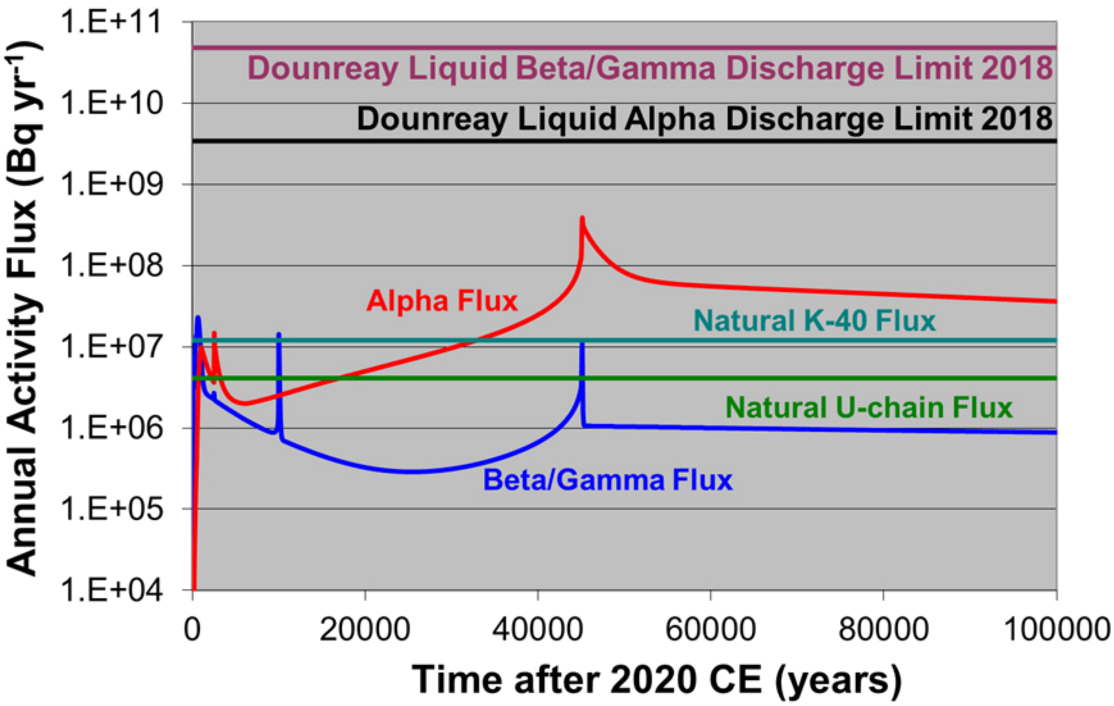


Figure 7.14: Calculated annual fluxes of total beta/gamma and alpha activity from the near-field (all vaults) to the geosphere [48]. Also shown are the 2018 annual liquid discharge limits for Dounreay (excluding specific limits for tritium, ^{137}Cs and ^{90}Sr) [45] and natural groundwater fluxes of U-chain activity and ^{40}K [315].

461 The 2020 total activity of the Case B and Demolition LLW best estimate inventory is around 1.7 x 10^{13} Bq of beta/gamma activity and 2.3 x 10^{12} Bq alpha activity (see Table 4.3). Only around 1% of this initial beta/gamma activity is released from the facilities over 100,000 years. An even smaller proportion of the activity initially consigned to the facilities reaches the biosphere (i.e. soils and waters that flora and fauna may contact). Owing to the very long half-lives of some of the alpha-emitting radionuclides, most of the initial alpha activity is released slowly over 100,000 years, albeit in the form of ingrown radionuclides rather than the originally disposed of radionuclides.

462 Figure 7.15 shows the calculated annual dose over 100,000 years to the Crofter RP from the Demolition LLW vaults only, compared to the total calculated annual dose from both the LLW and Demolition LLW vaults in Figure 7.10. As expected, the Demolition LLW inventory is a minor contributor to calculated dose compared to the LLW inventory, and the contribution decreases with time after closure.

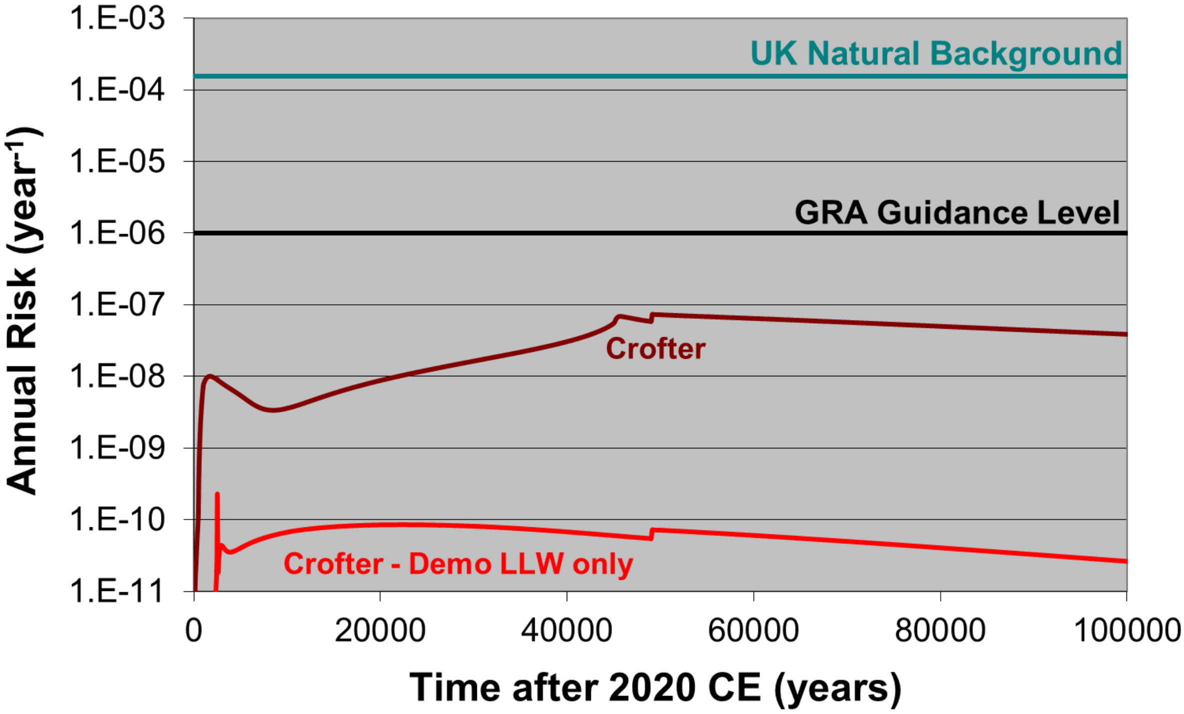


Figure 7.15: Calculated annual dose to the Crofter RP from the combined 2020 Case B and Demolition LLW best estimate inventory (reference calculation – Figure 7.10) and from the Demolition LLW best estimate inventory only.

463 Peak doses from the gas pathway are from radon inhalation, generated through the decay of ^{226}Ra in contaminated soil, to a resident in a house built downflow of D3100. The calculated annual dose, which assumes a one-to-one empirical relationship between the ^{226}Ra concentration in the soil and ^{222}Rn concentration in the indoor air peaks at 6 x 10^{-4} mSv y^{-1} after tens of thousands of years, equivalent to a peak conditional risk of 3.6 x 10^{-8} y^{-1}.

464 Note that the average measured ^{226}Ra concentration in soils of the D3100 study area is 61 Bq kg^{-1} (Table 6.10), which is several orders of magnitude higher than the calculated peak concentration of ^{226}Ra in the most contaminated soil in the Run 5 PA. Therefore, the highest dose resulting from radon generated from the decay of ^{226}Ra to a potential dweller living in a house built directly on the most contaminated soil would, accordingly, be several times smaller than the lowest radon dose from the natural background radium in that soil.

465 For ^{14}C, assuming realistic degradation rates, the calculated annual dose released from the LLW vaults in methane gas and then converted to carbon dioxide in the cap soil might be up to 4.3 x 10^{-4} mSv y^{-1}, equivalent to a conditional risk of 2.6 x 10^{-8} y^{-1}. This dose is calculated to occur from the start of the assessment to about

3,000 years. The calculated risk is principally related to ingestion of foodstuffs grown on the soil, with a minor additional contribution potentially occurring from inhalation of gas accumulating in a dwelling on the cap.

466 Modelling of radionuclide transport by gas has the potential to involve more complex considerations than modelling of radionuclide transport by groundwater, as two-phase flow is involved. The approach in the Run 5 PA is highly conservative, especially for indoor doses calculated for a RP resident in a house constructed above the cap:

- The details of how gas may move through the vaults and cap are highly uncertain and it is possible for all the gases to be trapped sufficiently long for releases to be zero (see [316] for example).
- Even if gas escapes to the surface, for any significant indoor dose to occur it must be assumed that a house having particular ventilation characteristics (leaky basement floor and remainder of structure that is poorly ventilated) is constructed exactly over the point of gas release at the time of the release.
- If the average probability of each member of a crofting community using the land where gas release occurs is taken into account, the calculated annual risk decreases to 3 x 10^{-11} y^{-1} from ^{14}C and 8 x 10^{-10} y^{-1} from radon.

467 Even with the conservative approach adopted for the Run 5 PA calculations, the calculated risks from the gas pathway are well below the GRA risk guidance level, even assuming exposure occurs with a probability of one. However, the likelihood of exposure is extremely low.

Disturbed performance – inadvertent human intrusion

GRA 6.3.36	**Requirement R7: Human intrusion after the period of authorisation.** The developer/operator of a near-surface disposal facility should assess the potential consequences of human intrusion into the facility after the period of authorisation on the basis that it is likely to occur. The developer/operator should, however, consider and implement any practical measures that might reduce the chance of its happening. The assessed effective dose to any person during and after the assumed intrusion should not exceed a dose guidance level in the range of around 3 mSv/year to around 20 mSv/year. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of years (prolonged exposures), while values towards the upper end of the range are applicable to assessed exposures that are only short term (transitory exposures).
GRA 6.3.39	Assess potential exposures of possible intruders to the radiological dose that might arise form a ranges of possible exposure scenarios. These scenarios should consider the exposures that arise from the potential exposures from the inventory of waste to be disposed of including any gaseous emissions from the waste such as radon; this should not include exposures to naturally occurring radon. Due to the large uncertainties associated with exposures to radon the developer should present these both aggregated with other exposures and individually.

GRA 6.3.40	Show that dose thresholds for severe deterministic injury to individual body tissues are unlikely to be exceeded as a result of human intrusion into a near-surface disposal facility.
GRA 6.3.49	Present assessments of radiation doses to individuals representative both of those undertaking intrusive activities and those who might occupy the site or the neighbourhood after intrusion. Explore the consequences of intrusion in a wider geographical sense and on the long-term behaviour of the disposal system. The assessments should take into account all radionuclides that may be present in the waste and all decay products making a significant contribution to dose. They should also take into account inhomogeneities in the waste.
GRA 6.3.52	Where potential doses around the dose guidance level may be possible for human intrusion scenarios as a result of long-lived radionuclides, use the results of the scenarios to propose facility-specific authorisation limits and conditions, such as inventory limits and allowable activity concentrations, supported with suitable arguments.

468 Figure 7.16 shows the total calculated annual dose to the RPs for the inadvertent human intrusion Disturbed Performance scenarios. The doses are calculated for the year after 2020 CE (the date of the 2020 inventory estimate – Section 4.3) that the excavation takes place (i.e. the dose at 100 years assumes the intrusion and residency all take place at 2120 CE, for 200 years at 2220 CE, and so on). The assumption is that the peak dose for any single event will occur at the time of the event. The waste activity used in each calculation is based on the activity in the near-field at the time of excavation, allowing for decay only, and no leaching of activity in groundwater. The assumption of no leaching is highly conservative (as shown in the leaching calculation undertaken for Run 3 [278, Figures 7.1 and 7.2]) and unrealistic over long timescales.

469 The consequences of the inadvertent human intrusion scenario are compared to the lower dose guidance level specified in GRA Requirement R7 [19]. This removes the need to speculate about the likelihood of the scenario. The calculated annual doses from inadvertent human intrusion immediately after 2020 CE are below the lower dose guidance level of 3 mSv y^{-1} (the level for prolonged exposures). Calculated doses fall rapidly in the first hundred years as the short-lived radionuclides in the facilities decay, and thereafter decline more slowly as only long-lived radionuclides remain in the facilities.

470 In the very long-term, calculated doses start to rise owing to ingrowth of radionuclides in the wasteform. In reality, doses will likely decrease due to leaching of activity by groundwater, a process that is not modelled in the calculations shown in Figure 7.16. The increase in calculated dose for the residency RPs relates to the ingrowth of ^{226}Ra from ^{234}U in the waste and a consequent calculated increase in ^{226}Ra in soil following intrusion. The redistribution of ^{226}Ra into the soil during intrusion removes the attenuation of radon by the cap in the Undisturbed Performance scenario and increases the potential for exposures to radon from the soil through accumulation in the dwelling of the residency RPs.

471 As shown in Figure 7.16, the main contributor to the dose for the Borehole Resident RP (generally the RP with the highest dose) is radon inhalation, which is shown

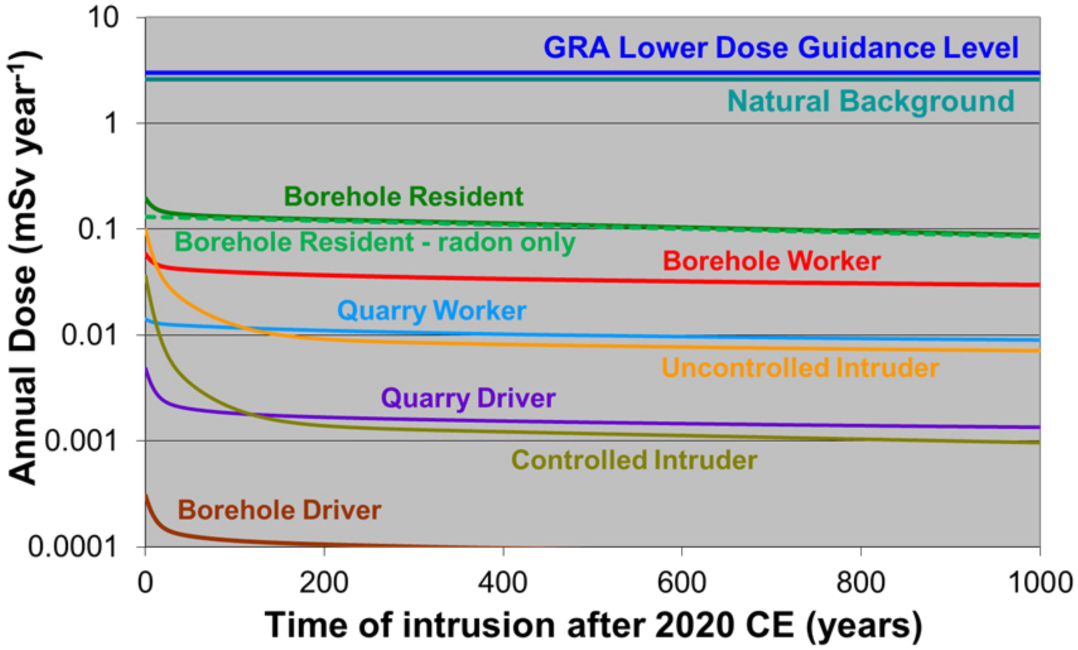
separately as requested in the GRA. The impact of other pathways for this RP are relatively minor, with these presented separately in the Run 5 PA report [48, Fig.7.2].

472 For the Borehole Worker RP (generally the RP with the second highest dose), ^{239}Pu, ^{240}Pu and ^{241}Am are the key contributors to dose, and the dust inhalation pathway is most significant, with lesser contributions from sediment ingestion and external irradiation, particularly from ^{137}Cs at early times.

473 The human intrusion calculations use the maximum activity at the vault scale for each radionuclide in any of the different waste vaults. Therefore, variation in inventory distribution between the different vaults will not cause an increase in the calculated dose. It is conceivable that greater exposure could be obtained from intrusion into a localised concentration of activity within a single vault. However, the borehole intrusion scenario assumes the drilling of two boreholes and it is considered reasonable to use an average waste activity across a vault based on the probability of the waste that might be intersected by each borehole. Uncertainty associated with higher-activity inventories is discussed further in Section 7.7.3.

474 The GRA [19, ¶6.3.40] requires the developer to show that the dose thresholds for severe deterministic injury to individual body tissues are unlikely to be exceeded as a result of human intrusion into a near-surface disposal facility. The dose threshold at which deterministic effects will occur depends on the type of tissue exposed. However, the HPA [68] notes that, for near-surface disposal facilities, the annual dose range of 3-20 mSv y^{-1} will "*ensure that the doses from inadvertent human intrusion are well below the level that could give rise to severe deterministic effects.*" Therefore, as all of the calculated effective doses from inadvertent intrusion into D3100 are below 3 mSv y^{-1}, the dose thresholds for severe deterministic injuries will not be exceeded and it is unnecessary to undertake further calculations to determine doses to individual organs.

(a)



(b)

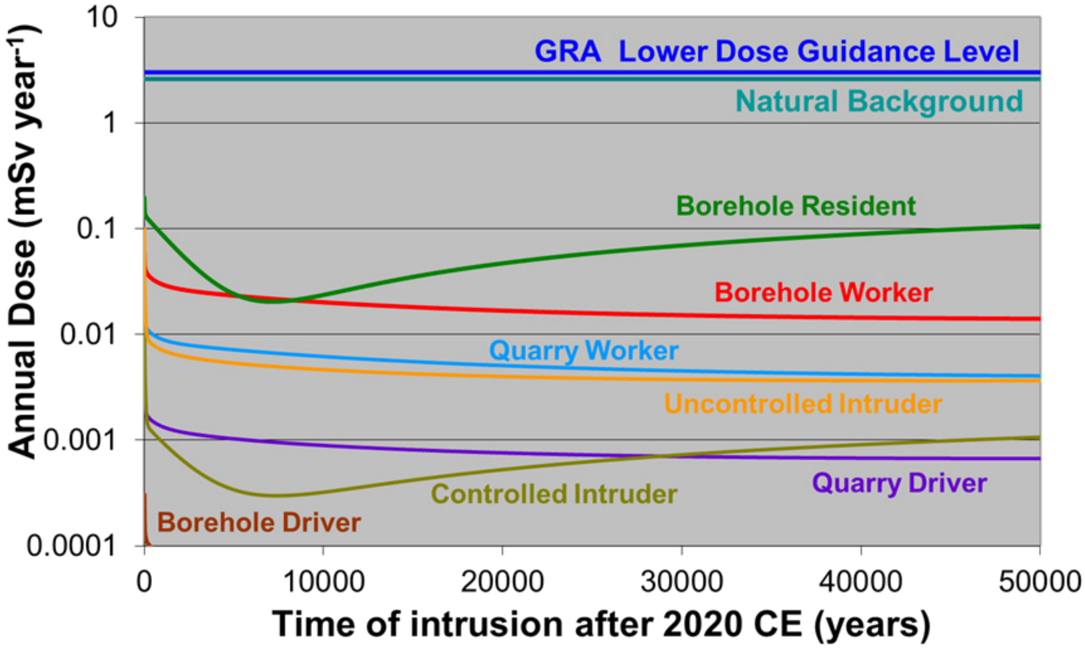


Figure 7.16: Calculated annual doses for the inadvertent human intrusion Disturbed Performance scenario over (a) 1,000 years and (b) 50,000 years, assuming no leaching of the inventory by groundwater prior to intrusion [48]. Annual doses are calculated at the time of intrusion. The GRA lower dose guidance level (3 mSv y^{-1}) for prolonged exposure as a result of inadvertent human intrusion [19] and the UK average annual dose from natural background radiation [312] are also shown. Note that this figure only shows calculated annual doses down to 1×10^{-4} mSv y^{-1}; the calculated doses to the Quarry Resident RP are below this level.

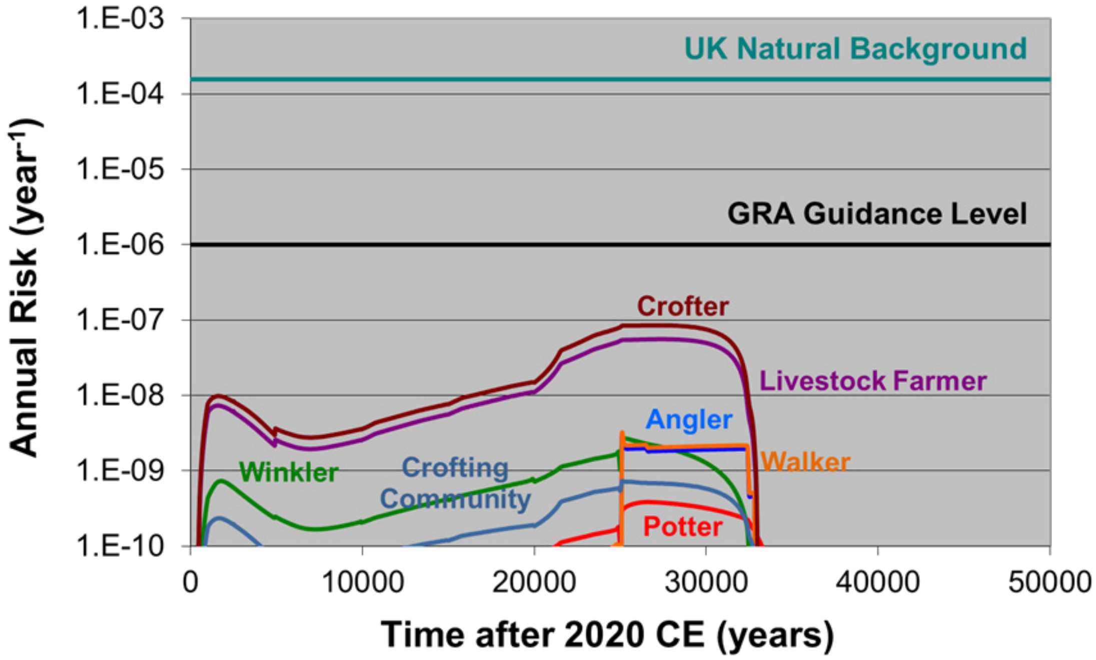
Disturbed performance – coastal erosion

475 Uncertainty in the coastal erosion rates has been considered in the Run 5 PA by undertaking two Disturbed Performance scenario calculations: one accounting for the reasonable upper estimate of the long-term average coastal erosion rate in [153] (10 mm y^{-1}) with erosion of the vaults by around 33,000 years; and the other accounting for erosion at the maximum erosion rate provided in [153] (50 mm y^{-1}) with complete erosion of the vaults by around 7,000 years. Results for these calculations are shown in Figure 7.17. For all RPs in both scenarios, the calculated risk is low and complies with the GRA risk guidance level.

476 The calculated annual risks to the RPs that make most use of the foreshore/cliff edge, and where the key exposure pathway is external irradiation or inhalation from the foreshore rock (e.g. Angler and Walker), increase during erosion of the vaults, although only at very low levels. This is because the concentration of the key radionuclides (^{226}Ra for external irradiation on the foreshore, ^{239}Pu for inhalation of dust) is slightly higher in the eroding wastes than in the geosphere.

477 There is no marked change in the calculated risks associated with exposure to marine waters during erosion. As the erosion front nears the vaults, the concentrations of key radionuclides (i.e. principally ^{226}Ra and its daughter, ^{210}Pb) in the geosphere groundwaters discharging to the coast and in the near-field porewaters discharging to the geosphere are similar, owing to the relative combination of retardation properties and water-to-solid ratios. Therefore, as the geosphere disappears there is no marked change in calculated risks as the near-field porewaters start to discharge directly to the foreshore. When the vaults are totally eroded, the concentrations of radioactivity in the coastal waters are maintained at a low level by exchange with the marine sediments that have received input from the material eroded onto the foreshore.

(a)



(b)

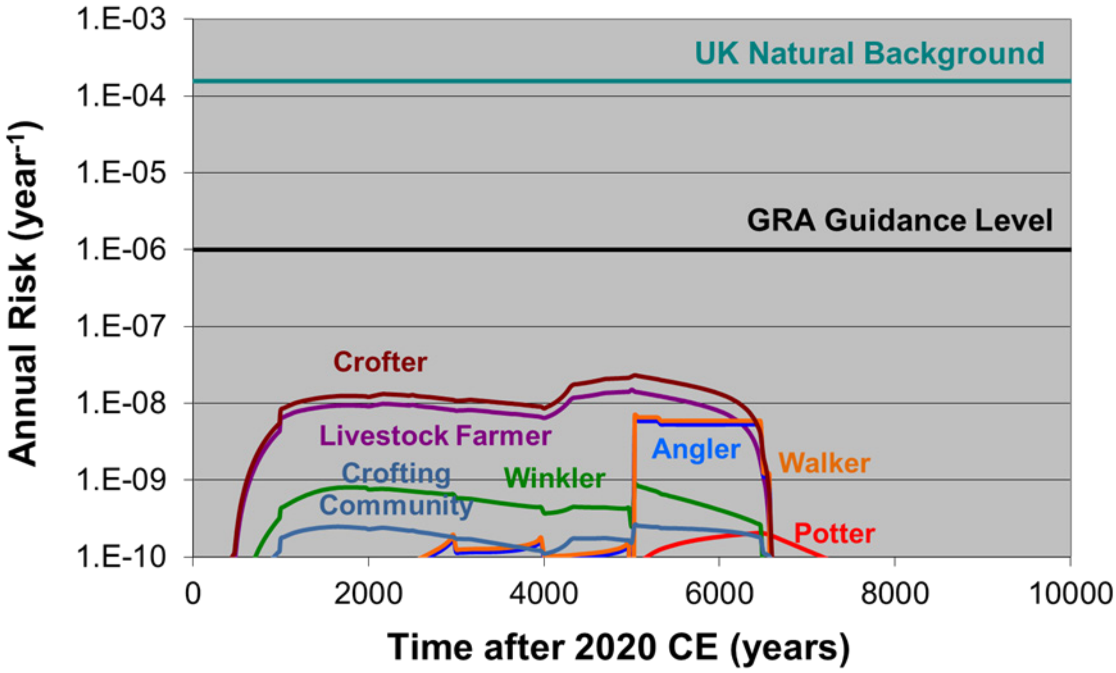


Figure 7.17: Calculated annual risks to the Undisturbed Performance scenario RPs resulting from the Disturbed Performance coastal erosion of D3100 [48]. (a) assumes an erosion rate of 10 mm y^{-1}; erosion of the vaults starts at around 25,000 years and is completed by around 33,000 years. (b) assumes an erosion rate of 50 mm y^{-1}; erosion of the vaults starts at around 5,000 years and is completed by 7,000 years.

Disturbed performance – groundwater extraction

478 Despite the extremely low probability of occurrence (as outlined in Section 7.4.3), the drilling of a borehole/well for drinking water has been considered in the Run 5 PA as a Disturbed Performance “what-if” scenario. To avoid the need for undue speculation about the probability of sinking a borehole/well, the location of the borehole/well with respect to the plume of contaminated groundwater downstream of the facilities, and the mix of groundwaters from different depths that the borehole/well samples, the Run 5 PA has used a highly stylised and conservative representation of the scenario. The potential consequences of the scenario have been calculated by assuming that drinking water is abstracted from a borehole/well drilled into the bedrock groundwater zones with the highest levels of contamination. Owing to the low groundwater flows in the Devonian bedrock, sufficient water is assumed to be available only to support the one Crofter family considered in the Undisturbed Performance scenario, that is, a larger group is not considered viable. A broader discretisation of the geosphere than is assumed in the PA models would dilute the concentrations and lower the calculated impacts.

479 The results for the groundwater extraction scenario are presented as a conditional risk (i.e. it is assumed that the exposure occurs) in Figure 7.18. However, given the extremely low probability of occurrence and the “what-if” nature of the calculation, the results are for information only and so are not compared to the performance measure of the risk guidance level. This removes the need to try to calculate an actual risk using a bounding probability for such a speculative event.

480 The results of the drinking water calculation are shown in Figure 7.18 for two cases: a shallow well is assumed to be dug into the weathered bedrock to a depth of a few metres; and a deep well is assumed to be drilled into the highest area of contamination in the unweathered bedrock at a depth of 10 - 20 m. Also shown for comparison is the UK average annual conditional risk (converted from dose assuming the exposure is received) from natural background radiation. The peak calculated risk from the deep well is comparable to this natural radiation level. The calculated risk might well be lower and more spread out over time, with the peaks of the PA results reflecting the spikes at around 45,000 years. The spikes are related to the modelling treatment applied in the PA that changes near-field retardation properties, which can vary over several orders of magnitude, linearly over time. This results in a calculated rapid release of radium and uranium towards the end of the chemical degradation of the near-field that may, in fact, be more gradual. However, while the spikes can be considered to be modelling artefacts, there is no clear scientific basis to model the change in retardation behaviour and, therefore, to meaningfully represent the performance of the system in any other manner.

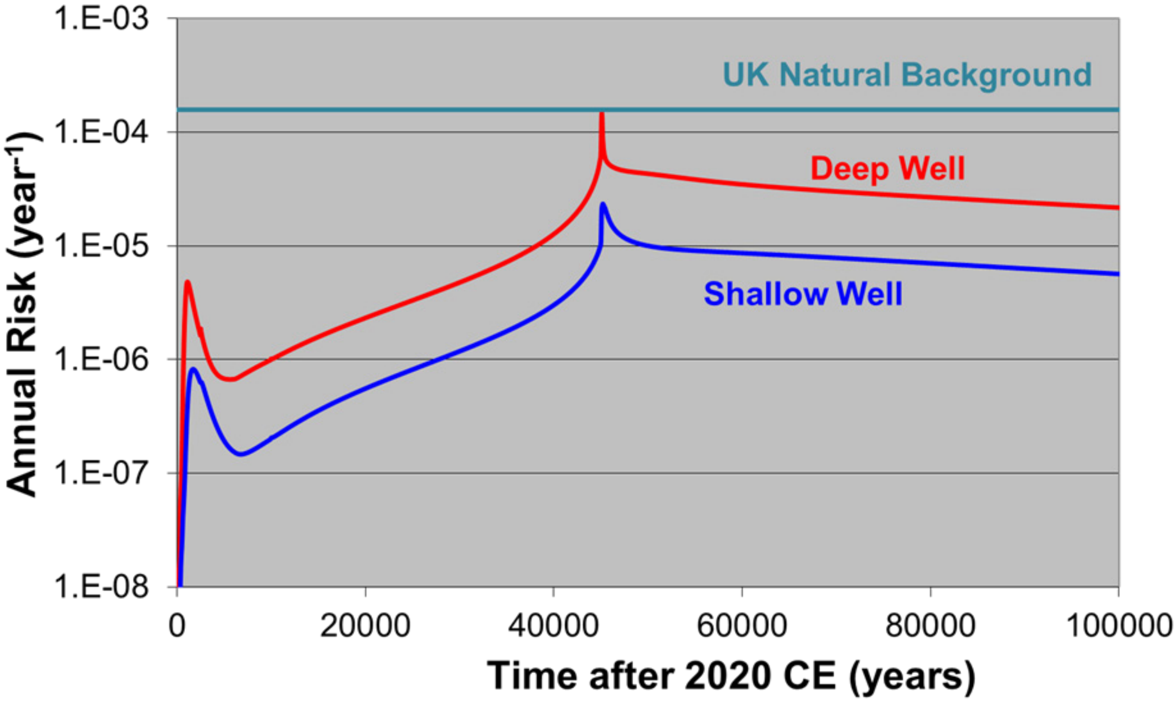


Figure 7.18: Calculated annual conditional risk from drinking water from a borehole/well into the most contaminated groundwater downstream of D3100 in the unaltered bedrock (deep well) and the altered bedrock (shallow well) [48].

Disturbed performance – ground rupture

481 In the ground rupture Disturbed Performance scenario "what-if" calculation, cracking of the grouted LLW and walls of the facilities through ground rupture is assumed to occur 200 years after closure. There is little difference in the results between the ground rupture calculation and the Undisturbed Performance scenario reference calculation in terms of the performance measure of calculated peak annual risk to the Crofter RP [48, Fig.7.6]. The ground rupture scenario does lead to greater fluxes of radioactivity leaving the near-field in the period up to 2,000 years after 2020 CE. However, after this time, the fluxes are almost identical to the Undisturbed Performance calculation and there is no significant difference in the magnitude of calculated peak annual doses in the long-term.

7.7.3 Uncertainty and sensitivity analysis

GRA 6.3.26(a)	Quantifiable uncertainties should be considered within a numerical risk assessment developed as part of an environmental safety case.
GRA 7.2.4	The environmental safety case should explain how uncertainties have been considered and will be managed in the future and demonstrate that there can be confidence in the environmental safety case notwithstanding the uncertainties that remain. It should also demonstrate that potential biases and their effects on the environmental safety case have been identified and eliminated or minimised.

GRA 7.3.8	Account for uncertainties explicitly, analyse their possible consequences and consider where they may be reduced or their effects lessened or compensated for. Uncertainties themselves are not obstacles to establishing the environmental safety case, but they do need proper consideration and including in the structure of the environmental safety case as appropriate.
GRA 7.3.15	Make clear which uncertainties have been quantified and applied to parameter values used in quantitative environmental safety assessments, and the methods used for carrying out the calculations.
GRA 7.3.16	Show that any simplifications adopted in the environmental safety assessments either have an insignificant effect on the outcome of the assessments, or have a conservative effect (i.e. do not lead to impacts being underestimated).
GRA 7.3.25	Show that the environmental safety case is not unduly sensitive to alternative interpretations or conceptual models.
GRA 7.3.27	Show that computational models have been used in an appropriate manner, giving the ranges of values for parameters outside which the results from a model cannot be relied on together with appropriate evidence.

482 Uncertainty and sensitivity analyses, which have included a mixture of probabilistic and deterministic analyses, have been conducted for each iteration of the D3100 project PA [157, App.2; 158; 48; 276; 278; 279].

Undisturbed performance

483 The Run 1 PA analyses undertaken by both PA contractors included sensitivity studies where multiple parameters were probabilistically sampled to identify which parameters were most significant to calculated performance measures. Both the EQ and GSL Run 1 PA analyses found that probabilistically sampling across all of the identified range of parameter uncertainty for the near-field parameters could cause a variation in calculated dose of up to three orders of magnitude [157, ¶189; 158, Fig.A4.4]. This variation was apparent at early times for the poorly retarded radionuclides and at late times for the actinide decay-chain daughters. However, the results using the best-estimate parameter values for near-field performance tended to lie towards the higher end of the range and in no cases did the parameter uncertainties cause the regulatory guidance levels to be exceeded.

484 Both the EQ and GSL Run 1 PA sensitivity analyses identified wasteform hydraulic conductivity as the key parameter that correlates with activity fluxes. As the wasteform becomes more permeable with time and the more retarded radionuclides start to be released, the wasteform degradation rate and the wasteform distribution coefficients increase in importance.

485 The uncertainty analyses for the subsequent D3100 PAs have considered uncertainties individually, focusing on the consequences of uncertainties in individual parameter sets and models. However, the next step of sampling across all of the parameter uncertainties to derive an expectation value of dose/risk that captures all uncertainties has not been attempted. More constraint than is possible on the correlations between sampled parameters would be needed to derive a meaningful result from such an exercise. The possible range in results from simultaneously

sampling all of the parameters is considered to be illustrated adequately by the Run 1 analyses.

486 The variation in calculated annual doses to the Crofter RP seen in response to uncertainties in near-field performance is less in the later iterations of the D3100 PA compared to Run 1. This is principally the result of two factors:

- The calculated annual doses after a few thousand years are all determined by the release rate of the parents of ^{210}Pb and ^{226}Ra (i.e. ^{230}Th and ^{234}U) from the near-field and their migration through the geosphere to the biosphere. Uncertainties in the behaviour of other radionuclides are largely unimportant in terms of the calculated annual doses to the Crofter RP in the long-term.
- Based on a review of the recent literature for PAs of other cementitious LLW disposal facilities, more cautious assumptions regarding the hydraulic degradation of the near-field have been made in later iterations compared to Run 1. The near-field is assumed to be well degraded after around 1,000 years and completely degraded after around 10,000 years, compared to 5,000 years and 40,000 years in Run 1. This results in significantly faster groundwater flows through the near-field at early times compared to Run 1, and the variation in releases of ^{234}U and daughters in the uncertainty analyses now tend to converge over time. If the performance measure being considered were different (e.g. releases of short-lived activity) then the assumed temporal variation in near-field hydraulic properties would become a more significant uncertainty.

487 Figure 7.19 illustrates that the uncertainty in the retardation properties in the near-field (calculated deterministically, using minimum and maximum values) creates just over an order of magnitude of variation in the calculated annual risk to the Crofter RP at times less than ca. 45,000 years. Variation in hydraulic degradation rates was not analysed in Run 5; however, the probabilistic calculation conducted in Run 4 [279, Fig.8.1] resulted in less than one order of magnitude variation.

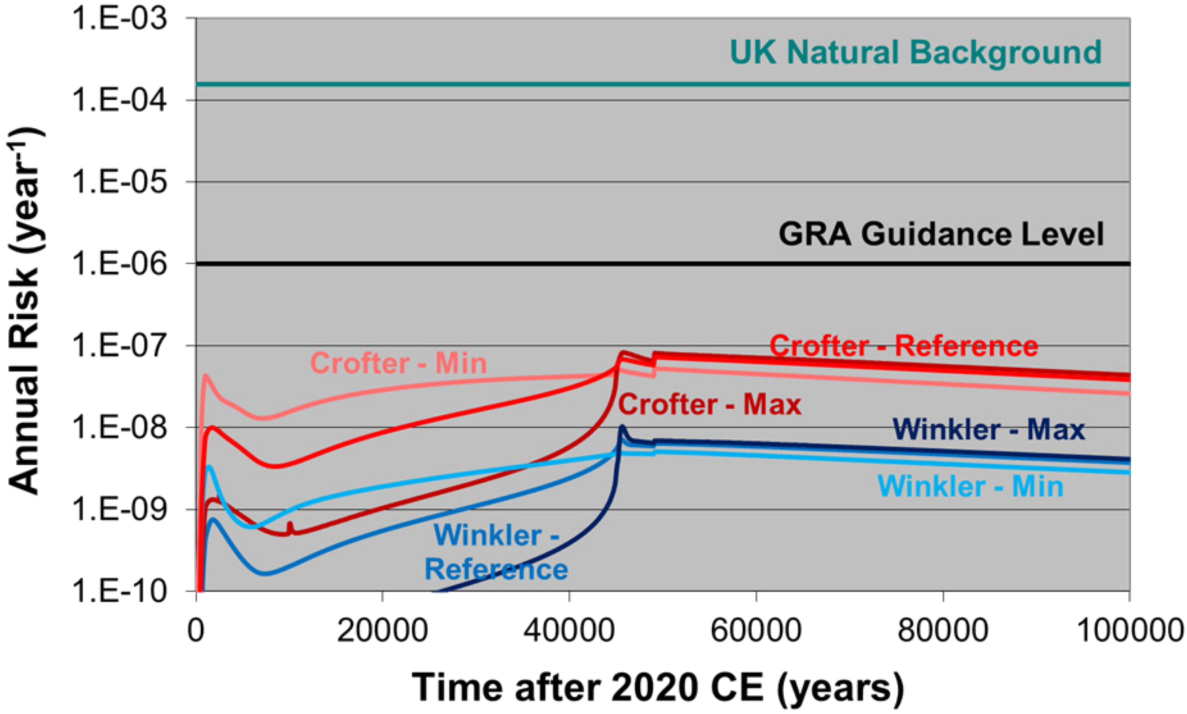


Figure 7.19: Calculated annual conditional risks to the Crofter and Winkler RPs from calculations assuming minimum and maximum values for the near-field LLW grout, Demolition LLW and barrier retardation properties [48]. The results for the Undisturbed Performance reference calculation are also shown for comparison.

488 Other uncertainties in near-field performance have limited significance:

- Changing the factor delaying releases from containers to allow for different package longevity or resaturation times was considered in Run 3 and was found to have little impact [278, ¶369]. In the first thousand years, low initial hydraulic conductivities of the wasteform and barriers act to limit releases, even if the radionuclides are assumed to be available for release immediately.
- For the Run 3 PA, a calculation was undertaken in which high solubility limits representative of oxidising conditions persist in the near-field over the entire assessment period (but maintaining near-field LLW grout retardation properties corresponding to reducing conditions), to evaluate the potential significance of solubility control on the PA results. Results showed that solubility controls are not significant to performance, and that the approach used in terms of solubility in the D3100 PA reference calculation is conservative [278, ¶375].
- A simulation in the Run 3 PA where the cap/lid was assumed to degrade twice as quickly as in the reference calculation (500 years) and where the final conductivity of the cap/lid was set high, thus allowing more upward flow of radioactivity from the wastes to the cap soil, showed only a small increase in calculated impacts to the Crofter RP [278]. In Run 5 (and 4), cap/lid

degradation is considered as part of a "what-if" bounding analysis that also considered poor performance of the enhanced geosphere (discussed below).

489 The Run 5 PA uses the latest D3100 2020 inventory estimate, for which two types of estimate for four inventory cases are derived. The Undisturbed Performance reference calculation uses the 2020 Case B and Demolition LLW best estimate inventories, which are considered to best represent the likely final inventory of D3100. As a bounding analysis of uncertainty in the inventory, an alternative calculation has also been conducted to consider the upper estimate of activity in the 2020 Case C and Demolition LLW inventories (see Section 4.3). The results of this calculation are shown in Figure 7.20. As might be expected, the results are higher for both RPs presented. However, the calculated risks are still well below the regulatory guidance level.

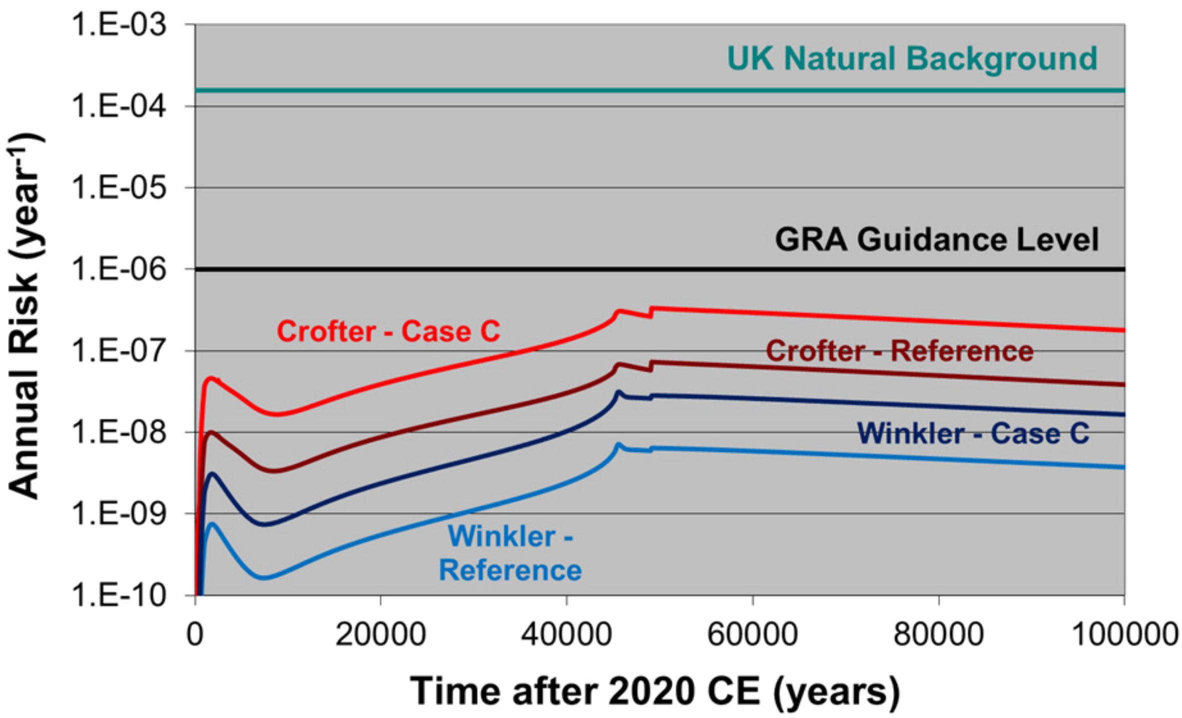


Figure 7.20: Calculated conditional risks to the Crofter and Winkler RPs for the Undisturbed Performance scenario reference calculation using the 2020 Case B and Demolition LLW best estimate inventories and an alternative calculation using the upper estimate of the 2020 Case C and Demolition LLW inventories [48].

490 For the geosphere, the Run 1 PA sensitivity analyses showed that high upward flow transfers and low distribution coefficients for the Devonian bedrock tend to promote migration of radionuclides into the soil, giving higher doses [157, ¶192; 158, ¶241]. The EQ analysis found that the distribution coefficients for the bedrock showed the strongest correlation with calculated activity fluxes in the geosphere and upward transfers showed the strongest correlation with doses in the biosphere [158, ¶249]. These findings were confirmed by the later PA uncertainty analyses. However, the introduction of the enhanced geosphere barrier has reduced the significance of the terrestrial pathway shown in the Run 2 and Run 3 iterations of the D3100 PA. A

deterministic uncertainty analysis of geosphere retardation in Run 5 shown in Figure 7.21 illustrates around an order of magnitude of variation in calculated annual conditional risk.

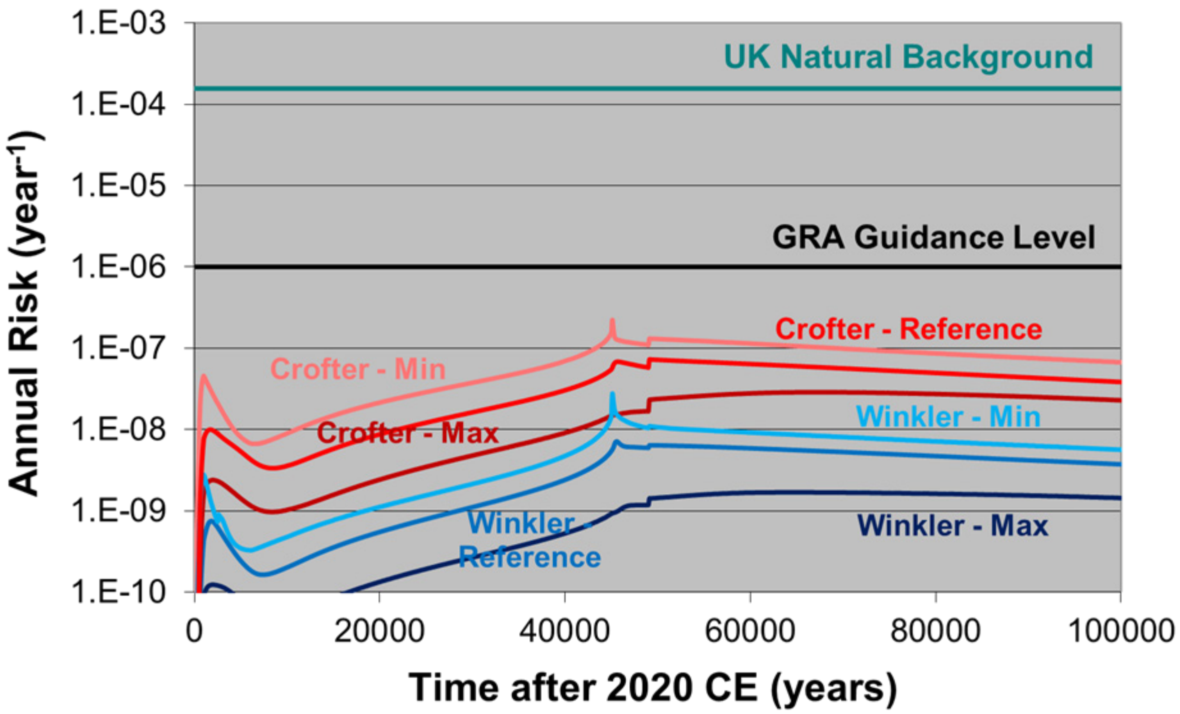


Figure 7.21: Calculated conditional risks to the Crofter and Winkler RPs from calculations using minimum and maximum parameter values for the geosphere bedrock and fracture retardation properties [48]. The results of the Undisturbed Performance reference calculation are shown for comparison.

491 A bounding "what-if" analysis was undertaken in Run 5 using flows from a variant calculation of the local-scale hydrogeological model [202], where the properties of the enhanced geosphere are set to reflect poor performance (low permeability). The analysis also assumes that the cap performance is poor (500 year lifetime) such that the final upward flow from the cap to the soil (0.01 m year^{-1}) is based on the default upward flow assigned by generalising the results from the non-performing enhanced geosphere calculation (Figure 7.22), which leads to the upward transfer of contaminated groundwater. The impact is much greater on the RPs that use the terrestrial food chain (Crofter and Livestock Farmer RPs), where the calculated conditional risks increase significantly compared to the Undisturbed Performance reference calculation. The calculation considering actual risks, represented by the Crofting Community RP, is still well below the regulatory risk guidance level.

492 It is important to note that the probability of this calculation, as indicated by its "what-if" or bounding nature, is extremely low. As noted in [202, p. 36], unrealistically low hydraulic conductivities are used for the enhanced geosphere in the local-scale hydrogeological model to develop the water balance for this calculation. Considered values are up to 40 times lower than in the reference calculation. Although the sub-soil layers of the enhanced geosphere are likely to undergo changes over time as the excavated material breaks down and it becomes more consolidated, the final

bulk hydraulic conductivity value is unlikely to become lower than the bulk value for the underlying weathered bedrock, as is considered for this calculation. It is suggested in [202, p. 36] that the degradation processes for some of the layers in the enhanced geosphere may actually result in increases in hydraulic conductivity over time.

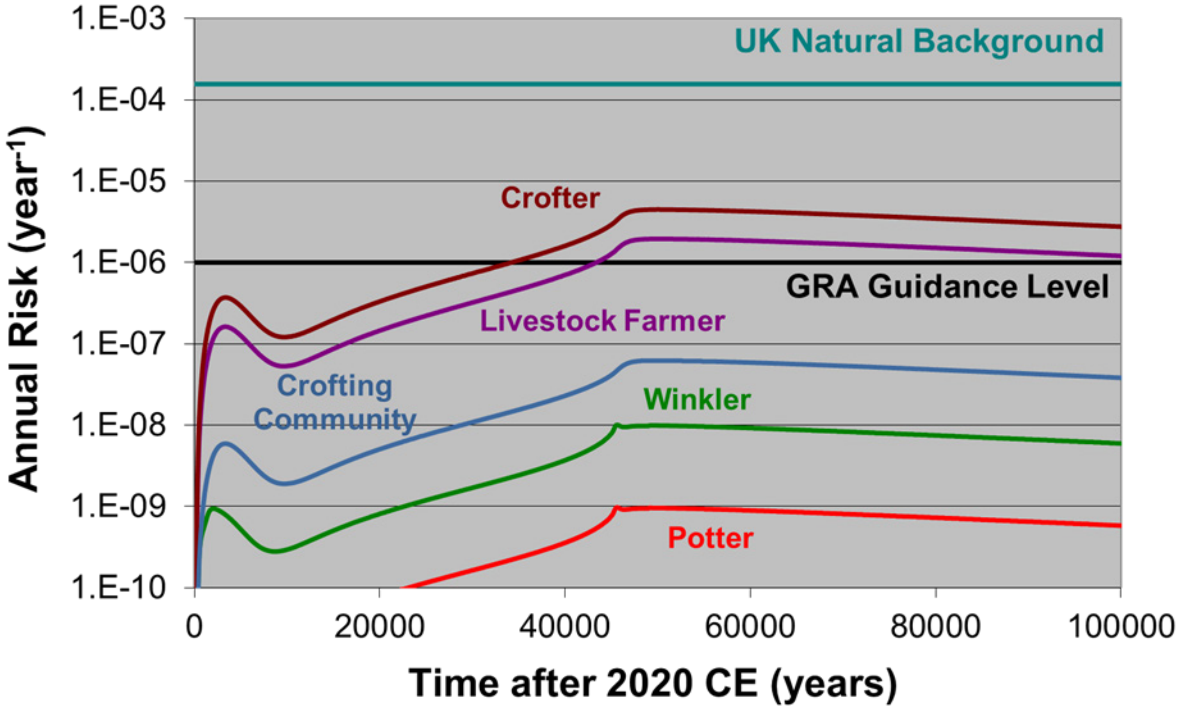


Figure 7.22: "What-if" calculation of conditional risk to the RPs for the Undisturbed Performance scenario reference calculation assuming poor performance of the cap and enhanced geosphere [48].

493 The effect of uncertainty in bedrock hydraulic conductivities on calculated annual dose is not as significant as for retardation and upward transfer:

- The hydrogeological role of faults is uncertain, but an uncertainty analysis was undertaken in Run 3 channelling 10% of the geosphere flow into the faults and assuming that 25% of the fault flow is to the near-surface groundwater zone. Owing to their size, faults are unlikely to be able to take a significantly higher proportion of the total geosphere flow. The uncertainty analysis resulted in only a slight increase in impact to the Crofter RP, suggesting that flow in faults is not likely to be radiologically significant [278, ¶389]. The installation of the enhanced geosphere layer further reduces the potential for any upward flow in faults reaching the ground surface.
- The effect of uncertainty in geosphere hydraulic conductivities on calculated annual doses (and thereby, conditional risk) to the Crofter RP was assessed in the Run 3 PA by undertaking a probabilistic analysis with 50 simulations sampling the range in unweathered Devonian bedrock and weathered bedrock hydraulic conductivities [278, Fig.8.9]. There was little sensitivity in calculated dose to the range in hydraulic conductivity. In the Run 4 and 5 PAs, horizontal flows in the geosphere are specified on the

basis of local-scale hydrogeological modelling rather than being calculated directly from the hydraulic conductivities and hydraulic gradient. However, the uncertainty in conductivities can also be considered to be captured implicitly in the analysis of uncertainty of travel times determined by the fracture properties in the bedrock. As part of the Run 5 PA calculations, a deterministic uncertainty analysis considering minimum and maximum fracture spacings within the unweathered bedrock was undertaken. The results show that fracture spacing has little impact on annual risk [48, Fig.8.4].

494 In regards to the biosphere, the Run 1 PA found that calculated doses were only moderately sensitive to variation in biosphere parameter values; even when values were varied by more than an order of magnitude, the doses ranged by a little more than one order of magnitude between the 1st and 99th percentile [158, ¶251]. This is because the combination of exposure pathways being considered resulted in doses from a range of biosphere materials. The key processes were found to be associated with the concentration of contaminants in the soils and their transfer into foods. In the Run 4 PA, a probabilistic analysis sampling the range in retardation properties for soil and the biosphere uptake factors for the main foodstuff pathways identified in the Run 1 and Run 2 PAs of livestock meat (including uptake from pasture) and consumption of potatoes indicated only a small variation in the calculated impact to the Crofter RP [279]. In Run 5, a deterministic uncertainty calculation considering just soil retardation produced similar results [48, Fig.8.6].

495 In the D3100 project PA, RP behaviour is assumed constant over time. The relationship between diet and calculated dose will be linear. However, the effects of uncertainties associated with diet are considered to be lower than the effects associated with radionuclide transport and retardation. In general, calculated doses could vary a few-fold with assumptions about diet, but generally only downwards as the D3100 PA RPs make maximal use of contaminated resources.

496 In regards to environmental change, the Run 1 PA sensitivity analyses illustrated that the PA results are robust to different assumptions on their timing and magnitude [157, ¶172; 158, ¶47 and 196]. The Run 2 and 3 PA analyses considered different erosion rates/durations and showed that more rapid erosion generally lowered the calculated annual dose. This is because erosion removes the contaminated ground that is assumed suitable for livestock and arable farming between the facilities and the coast, and this is a key exposure pathway. However, the introduction of the enhanced geosphere barrier has reduced the significance of the terrestrial pathway, and more rapid erosion now has limited impact on calculated doses. Exposure to more highly contaminated material on the foreshore and in the marine environment does tend to increase calculated doses across some of the RPs, such as the Angler and Walker, but only by a small amount. This is shown by the results for the coastal erosion Disturbed Performance scenario in Figure 7.17. In Run 5, the impact of no erosion has also been considered. This resulted in a slight increase in impacts to the terrestrial pathway (represented by the Crofter RP), as none of the contaminated area was eroded, but no impact on the marine pathway (represented by the Winkler RP) [48, Fig.8.7]. In all cases, the calculated impacts remain below the regulatory guidance level.

497 For ^{14}C gas releases, the rate of anaerobic degradation will impact releases from D3100. The rate of anaerobic degradation of cellulose under different conditions has been investigated in some detail for the Waste Isolation Pilot Plant PA in the US. The results are summarised in [317, Tab.6.1], from which the long-term rate supported by experimental evidence is used in the reference case for the cellulose and plastics/rubbers material types considered in the D3100 gas model. When considering the worst case material degradation rates and incorporation of all of the ^{14}C in the waste into the gas phase, calculated doses are around 2.2 x 10^{-2} mSv y^{-1} equivalent to a conditional risk of 1.3 x 10^{-6} y^{-1}. However, this rate of degradation is not credible as the long-term rate, both on the basis of experimental evidence [317] and consideration that the cellulose and plastics inventory would be rapidly consumed. As such, the conditional risk based on the dose from gaseous ^{14}C can be expected to remain below the risk guidance level over the range of uncertainty in the cellulose degradation rate.

498 The variation in risks from ^{222}Rn due to uncertainties in groundwater-mediated releases can be inferred from the other analyses presented in this section. This is because ^{226}Ra is one of the key radionuclides contributing to the conditional risk to the Crofter RP for these analyses. Therefore, variations in the peak conditional risk in these analyses are highly likely to be mirrored by similar variations to the peak conditional risk from ^{222}Rn exposure incurred in a house built directly on the most contaminated soil.

499 Calculations for the gas pathway using the best estimate of the degradation rate and the Case C and Demolition LLW upper estimate inventories are considered in the Run 5 PA. Conditional risks of 5.3 x 10^{-7} y^{-1} and 1.6 x 10^{-7} y^{-1} are calculated for ^{14}C and ^{222}Rn, respectively; both below the regulatory guidance level.

500 Owing to the very low calculated annual doses, uncertainty analyses for the Demolition LLW vaults in isolation have not been undertaken recently. Sensitivity studies were conducted for a separate Demolition LLW facility using the Run 1 PA models. The performance of the near-field is key to determining calculated peak annual doses. Considering the wasteform to have the same hydraulic properties as the vault walls (the engineered barrier), the EQ Run 1 PA found that the radionuclide flux (and performance) of a below-surface Demolition LLW facility was most sensitive to the hydraulic conductivity of the engineered barrier, the time at which the hydraulic conductivity of the engineered barrier starts to degrade, and the wasteform K_d values [318, Ch.6]. The performance of the cap in preventing upward transfer of activity was also significant in the GSL analysis [319, Ch.7].

Disturbed performance

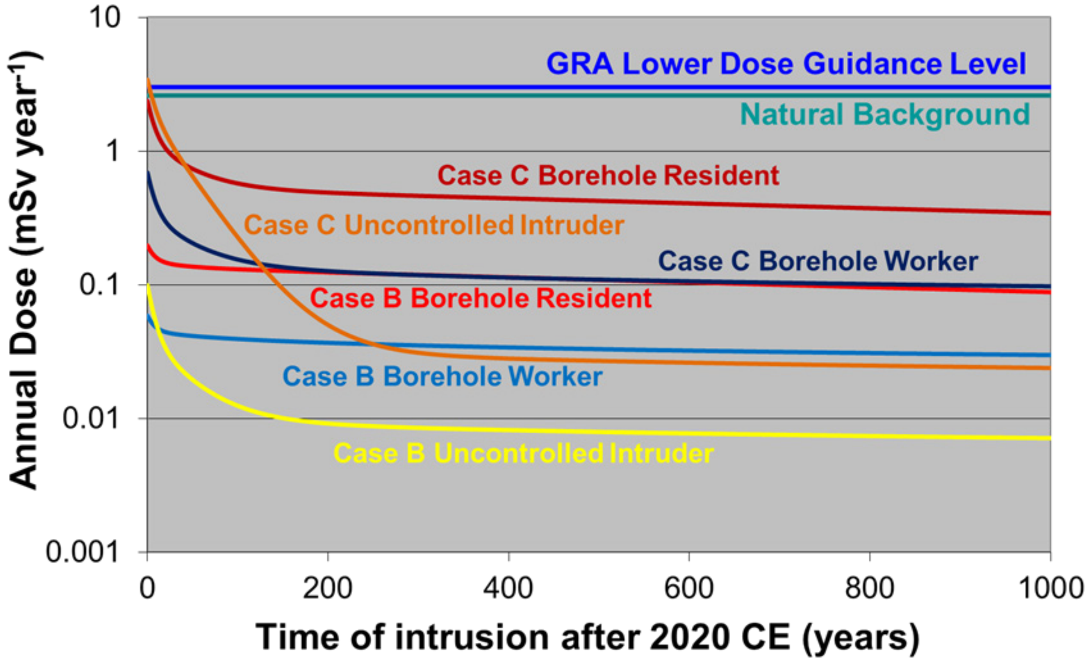
501 The main uncertainties related to inadvertent human intrusion are the activity of the waste, the volume of waste that is disturbed (i.e. the nature and scale of the intrusion), the subsequent redistribution of the waste in the environment, and the effects of institutional control.

502 In regards to activity uncertainty, the Run 5 PA has undertaken a human intrusion uncertainty analysis using 2020 Case C and Demolition LLW upper estimate inventory (Table 4.3). The results are shown in Figure 7.23; these indicate that D3100 would still comply with the regulatory lower dose guidance level of 3 mSv y^{-1}

with the higher inventory, although not until after 2022 CE for the Uncontrolled Intruder RP.

503 It should also be noted that institutional controls could anyway be used to prevent large-scale intrusive activities in the near-term while short-lived radionuclides (e.g. ^{137}Cs and ^{90}Sr) decay. This might be justified in terms of ensuring doses are as low as reasonably achievable. Alternatively, even higher inventories of such short-lived radionuclides could be accepted if institutional control is applied. The need for institutional control is discussed in Section 11 of this ESC.

(a)



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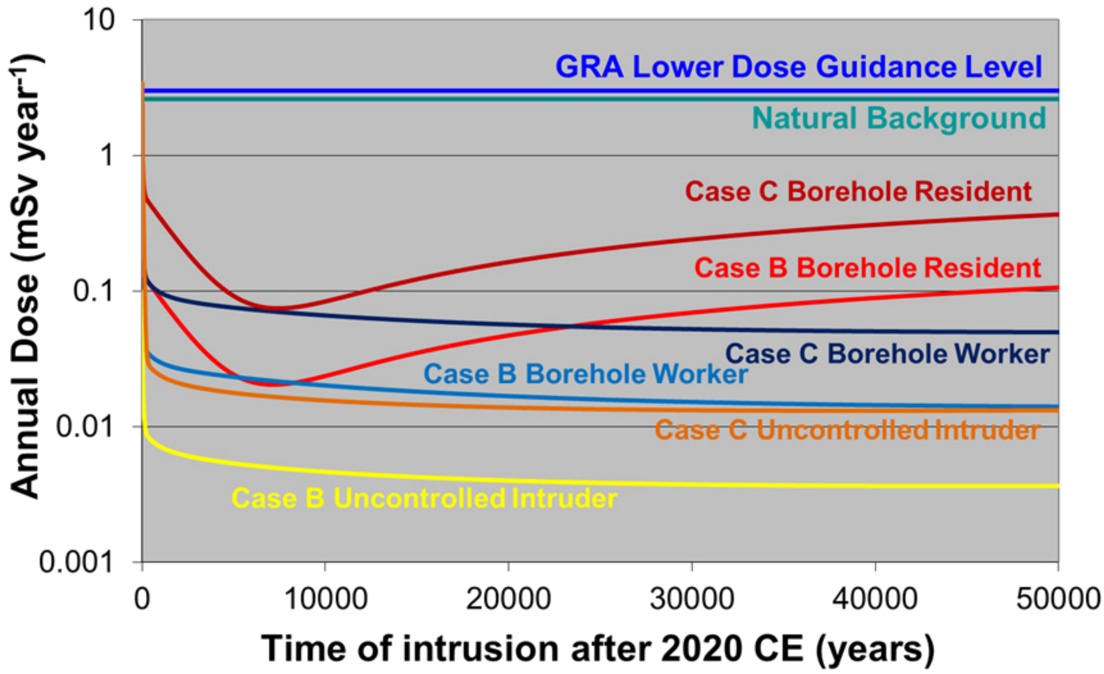

Figure 7.23: Calculation of peak annual doses for the inadvertent human intrusion Disturbed Performance scenario over (a) 1,000 years and (b) 50,000 years, assuming no leaching of the inventory by groundwater prior to intrusion [48]. Results are presented for the Case B and Demolition LLW best estimate inventories and the Case C and Demolition LLW upper estimate inventories. Annual doses are calculated at the time of intrusion as shown on the *x* axis.

504 In regards to the other key human intrusion scenario uncertainties, the Run 5 PA captures these by considering the range of plausible intrusion activities over the considered scenarios. Therefore, the calculated doses shown in Figure 7.16 are considered to be robust to such uncertainty. It is possible that the intruder RPs could come into contact with a localised volume of waste with a higher activity than the average waste activity across the LLW vaults [9, ¶6.3.49]. But, as noted in Section 7.7.2, localised higher concentrations of key radionuclides are unlikely to challenge compliance with the GRA lower dose guidance level.

505 Figure 7.17 shows the effects of uncertainties in erosion rates for the coastal erosion Disturbed Performance scenario. The earlier that erosion of the facilities occurs, the higher the calculated dose to users of the foreshore and the marine environment, but calculated doses are, in all cases, below the regulatory guidance level.

7.8 Skyshine

7.8.1 Introduction

506 The main pathway for possible exposure of the public during operation of D3100 is through skyshine. Skyshine is radiation arising from interactions of gamma rays and x-rays (photons) with air molecules. Gamma rays and x-rays emitted upwards from the vaults could result in doses to the public from skyshine.

7.8.2 Approach

Previous Assessment

507 An assessment of the potential doses arising via skyshine from D3100 was undertaken previously [320] in support of ESC 2010 [29]. This work largely remains applicable in 2020 and forms the basis for the consideration of impacts from skyshine described here.

508 Initial calculations to assess the significance of different radionuclides and decay periods were undertaken in the 2010 skyshine assessment. The results of these initial calculations identified the key radionuclides contributing most significantly to skyshine doses for consideration in subsequent calculations. The process followed for determining the key nuclides and applicability of the previous 2010 assessment in 2020 is described in Section 7.8.3.

509 The 2010 assessment included baseline calculations assuming the inventory to be homogeneously distributed throughout a single vault. Separate calculations were undertaken for vaults containing LLW and Demolition LLW, and a series of different receptor locations was assessed. Whilst doses from all of the vaults combined were not calculated explicitly, doses from single vaults were found to be sufficiently low that the combined effect would also be small if multiple vaults were open at the same time. Sensitivity calculations were performed to assess the effects of different waste densities, different numbers of HHISO container layers in the vaults, and the presence and thickness of a vault roof.

510 To assess the effects of variability in waste loading, the 2010 assessment also calculated skyshine dose rates for individual containers containing higher activities than the average value. These calculations used extremely conservative assumptions about the activity that could be disposed of in a single container based on the requirements in the WAC relating to external surface dose rates. The calculations considered a single HHISO container having the maximum possible activity for each of the key radionuclides that still met the surface dose rate criteria. The approach was highly conservative, as the maximum activity was derived for each radionuclide in turn rather than the combined activity having to satisfy the surface dose rate limits.

511 Results of the 2010 assessment demonstrated all potential doses from skyshine to be small and well within regulatory constraints, with potential annual doses to the most exposed members of the public from a single vault orders of magnitude below the dose constraint of 0.3 mSv y^{-1} specified in the GRA and the 0.15 mSv y^{-1} dose constraint recommended by the HPA for exposure to the public from a new disposal facility for radioactive waste [68]. Potential doses for disposal of a single container that meets the surface dose rate criteria in the WAC were found to be comparable to the doses for an entire vault of containers at the average activity. Waste density was the only sensitivity found to have a significant effect on the calculated results, with potential doses from skyshine from ungrouted LLW shown to be approximately double those from grouted LLW (but still small and within regulatory constraints).

Approach for 2020

512 A qualitative approach to assessment of impacts from skyshine is undertaken here, based on the previous work described above. Approximate dose rates from skyshine assuming the inventory is homogeneously distributed over the whole vault have been estimated by scaling the 2010 results for the key radionuclides using the updated 2020 LLW inventory (Section 4.3). A comparison of inventory differences between the inventory used in the 2010 assessment and the 2020 inventory has been undertaken to ensure the list of key radionuclides remains suitable. This comparison is documented in Section 7.8.3.

513 The individual container calculations performed as part of the 2010 assessment were independent of the inventory (as they were based on the maximum possible surface dose rate) and so these remain unchanged and are still applicable now. Therefore, these are also included in Section 7.8.3.

514 Doses to members of the public are estimated assuming that they are present at the field boundary south-east of the site (410 m away); this is the closest location that a member of the public might spend a reasonable amount of time. Doses to workers are also estimated assuming that they spend half their time located 25 m away and the other half 100 m away. These doses are calculated partly to understand the sensitivity to distance and partly to indicate if there are any issues for operations. However, members of the public would not normally have access at these distances. All scaled dose rates and estimated annual doses are documented in Section 7.8.4.

7.8.3 Radionuclides

515 The 2010 assessment was undertaken using the commercial MicroSkyshine software from Grove Software Inc. [320, ¶15]. MicroSkyshine includes a database of photon energies which is used to construct a photon energy and activity profile for a specified set of radionuclides. Although a full inventory could be used to define the source term for MicroSkyshine, it is more efficient to limit the inventory to the key radionuclides that contribute most to the skyshine pathway. Hence the first set of calculations undertaken as part of the 2010 assessment used different sets of radionuclides from the full inventory to establish the key radionuclides for use in the subsequent calculations. The relative abundancies of radionuclides used were based on the average composition of LLW as reported in the 2009 inventory report [122]. The JEFF 3.1 nuclear database [321] was used to identify radionuclides with the most significant gamma energies and with significant inventories, or with parents with significant inventories, which were included in a set of MicroSkyshine scoping calculations.

516 These calculations demonstrated that limiting the radionuclides considered to a set of four (^{60}Co, ^{137}Cs (with its ^{137m}Ba daughter), ^{108m}Ag and ^{226}Ra (with daughters)), and limiting the ingrowth calculations to five levels of daughters, gave a less than 0.5% reduction in calculated skyshine dose rates compared to the results calculated using all radionuclides and daughters. Eliminating ^{108m}Ag and ^{226}Ra from the set still had only a small effect on the calculated skyshine dose rates, showing that the dose rates were largely determined by the activities of ^{60}Co and ^{137}Cs. However, ^{108m}Ag and ^{226}Ra were included in the subsequent dose calculations for completeness as they are high gamma emitters.

517 Comparison of the radionuclides included in the 2020 and 2009 inventories identified one radionuclide with reported activity in 2020 that was not reported in 2009: ^{22}Na. The gamma energy for ^{22}Na is less than that for ^{60}Co, though is greater than that for ^{137}Cs (with ^{137m}Ba) [321]. However, the contribution to the total activity from ^{22}Na in the 2020 inventory is very small compared to the contributions from ^{60}Co or ^{137}Cs; for LLW excluding the Pits waste (Case A in the 2020 inventory [47]) ^{22}Na contributes ~0.01% to the total activity compared to ~16% and ~15% for ^{60}Co and ^{137}Cs, respectively. Based on this, and the short half-life of ^{22}Na (2.6 years), it is highly unlikely that its addition would have much influence on doses from skyshine and so its exclusion from the 2010 assessment does not invalidate the qualitative approach followed here.

518 In addition to comparing the 2009 and 2020 LLW inventories for newly included radionuclides, the inventories have also been compared to identify radionuclides with significantly increased activities in 2020 which could potentially impact doses from skyshine. Ten additional radionuclides (excluding those already included in the list of key nuclides in the 2010 assessment) were identified as gamma emitters with large increases from the 2009 inventory to the 2020 inventory. Of these nuclides, according to the JEFF 3.1 database [321], only one has gamma energy larger than both ^{60}Co and ^{137}Cs, ^{110m}Ag, while two have gamma energies larger than ^{137}Cs though smaller than ^{60}Co (^{152}Eu and ^{154}Eu). However, these three nuclides all have much smaller inventories than ^{60}Co and ^{137}Cs: ^{110m}Ag contributes ~0.02% to the total LLW activity excluding the Pits waste (Case A [47]) and has a half-life of less than a

year, and ^{152}Eu and ^{154}Eu contribute ~0.3% and ~0.6% respectively. All of the remaining nuclides in the identified list have both lower gamma energies and lower inventories and are therefore highly unlikely to have a non-trivial impact on calculated doses from skyshine.

519 In light of this review, the list of radionuclides considered in the 2010 assessment remains suitable.

7.8.4 Estimated doses from skyshine

Scaled dose rates

520 Baseline calculations undertaken in the 2010 assessment [320] assumed that the LLW, LLW Pits and Demolition LLW inventories are homogeneously distributed throughout the respective waste vaults. The results of these calculations have been scaled using the updated 2020 inventory, as discussed in Section 7.8.2. A comparison of the inventories for the key radionuclides is given in Table 7.3, and the linearly scaled dose rates in Table 7.4 to members of the public and Table 7.5 and Table 7.6 to workers. The scaling factor has been calculated from the difference in total activity for the four radionuclides; no weighting has been applied to account for the different gamma energies. Note that these calculations assume a member of the public is present 410 m from the vault, which corresponds to the field boundary south-east of the site, and at a height of 5 m. Workers are assumed to spend half their time 25 m away from the vault and the other half 100 m away, at a height of 1 m. A waste density of 2,400 kg m^{-3} is assumed for LLW, which is assumed to be grouted and disposed of in HHISO-type containers, and a waste density of 1,350 kg m^{-3} for Demolition LLW, which is assumed to be disposed of in unconditioned bags. A steel roof of 2 mm thickness is assumed to be present.

521 For LLW 1 and 2, Table 7.3 shows that the ^{60}Co activity has increased by an order of magnitude in the 2020 inventory, whereas the ^{137}Cs activity has approximately halved. The combined total activity of all four radionuclides considered has reduced by ~1.5% and so the linearly scaled dose rates for LLW 1 and 2 have shown a corresponding decrease (Table 7.4 to Table 7.6). In contrast, for LLW 3, the linearly scaled dose rates using the 2020 inventory show a large increase compared to those calculated with the 2009 inventory. This is a result of the large increases in ^{137}Cs and ^{226}Ra activities greatly outweighing the decrease in ^{60}Co activity. For Demolition LLW the linearly scaled dose rates are approximately double those calculated in 2009. This is largely due to the re-categorisation of one particular waste stream from LLW to Demolition LLW, which is responsible for the increase in ^{137}Cs activity shown in Table 7.3.

Table 7.3: Comparison of activities used in the 2010 skyshine assessment from DRWI 2009 with the corresponding activities from the 2020 LLW inventory [48].

Inventory	Radionuclide	Total activity (Bq)	
		DRWI 2009	2020 Inventory
DRWI 2009: LLW 1 and 2 2020 Inventory: Case A	^{60}Co	2.81E+11	1.46E+12
	^{137}Cs	2.73E+12	1.41E+12
	^{108m}Ag	6.01E+05	1.20E+07
	^{226}Ra	3.57E+09	9.91E+10
DRWI 2009: LLW 3 2020 Inventory: Case B – Case A (Pits)	^{60}Co	5.42E+09	2.63E+09
	^{137}Cs	1.69E+12	2.65E+12
	^{226}Ra	5.43E+09	1.08E+10
Demolition LLW	^{60}Co	4.12E+09	2.93E+09
	^{137}Cs	1.87E+11	3.79E+11

Table 7.4: Dose rates to members of the pubic from skyshine linearly scaled from those calculated in the 2010 assessment [320] based on the change in activities between DRWI 2009 and the 2020 LLW inventory. All results given assume the receptor is 410 m away at a height of 5 m relative to the top of the vault walls (at the field boundary south-east of the site).

Inventory	Skyshine dose rate ($\mu Sv\ h^{-1}$)	
	DRWI 2009	2020 Inventory
DRWI 2009: LLW 1 and 2 2020 Inventory: Case A	1.87×10^{-4}	1.84×10^{-4}
DRWI 2009: LLW 3 2020 Inventory: LLW Pits	1.83×10^{-4}	2.87×10^{-4}
Demolition LLW	4.54×10^{-5}	9.08×10^{-5}

Table 7.5: Dose rates to workers from skyshine linearly scaled from those calculated in the 2010 assessment [320] based on the change in activities between DRWI 2009 and the 2020 LLW inventory. All results given assume the receptor is 25 m away at a height of 1 m relative to top of the vault walls.

Inventory	Skyshine dose rate (μSv h^{-1})	
	DRWI 2009	2020 Inventory
DRWI 2009: LLW 1 and 2 2020 Inventory: Case A	3.61×10^{-2}	3.56×10^{-2}
DRWI 2009: LLW 3 2020 Inventory: Pits	4.44×10^{-2}	6.95×10^{-2}
Demolition LLW	1.09×10^{-2}	2.17×10^{-2}

Table 7.6: Dose rates to workers from skyshine linearly scaled from those calculated in the 2010 assessment [320] based on the change in activities between DRWI 2009 and the 2020 LLW inventory. All results given assume the receptor is 100 m away at a height of 1 m relative to top of the vault walls.

Inventory	Skyshine dose rate (μSv h^{-1})	
	DRWI 2009	2020 Inventory
DRWI 2009: LLW 1 and 2 2020 Inventory: Case A	8.93×10^{-3}	8.79×10^{-3}
DRWI 2009: LLW 3 2020 Inventory: Pits	1.02×10^{-2}	1.60×10^{-2}
Demolition LLW	2.47×10^{-3}	4.93×10^{-3}

Single container dose rates

523 The 2010 assessment calculated skyshine dose rates from individual containers containing extremely conservative activities based on the maximum surface dose rate criteria in the WAC. The WAC require that the maximum radiation level from the external surface of a LLW waste container accepted for disposal in D3100 must not exceed 7.5 mSv h^{-1}. The corresponding dose rate for bagged waste should not exceed 2 mSv h^{-1}. Maximum possible activities for each radionuclide considered were derived from these criteria [320, §2]. Two sets of calculations were undertaken assuming that the individual container is placed in the top layer of the vault and assuming it was shielded by a layer of containers. For each of these, calculations were undertaken for the container placed at the edge of the vault and in the middle. Due to the extremely conservative nature of these calculations, receptors were assumed to be 410 m away and closer receptors were not assessed. Results of these calculations remain applicable in 2020 and are given in Table 7.7 and Table 7.8 below.

524 The results for LLW in Table 7.7 show that the potential skyshine dose rates for a single container, which meets the surface dose rate criteria and is placed in the top layer of the vault, are comparable to the scaled 2020 dose rates to a member of public for an entire vault of containers at the average activity (Table 7.4). For Demolition LLW the dose rates from the single container calculations (Table 7.8) are much lower than the scaled dose rate given in Table 7.4, as a result of the increased inventory of Demolition LLW in 2020.

525 These results also show that the location of a single higher-activity container can be important. At the edge of the vault, the vertical vault wall provides some shielding from skyshine. More important is the effect of even a single container above the higher-activity container, which even for bagged waste provides sufficient shielding to make the dose rates insignificant.

526 It is unlikely that containers will have activities comparable to those assumed in the calculations. Other waste acceptance criteria, such as limits on overall radionuclide concentrations, will generally be more constraining than the surface dose rate criteria.

Table 7.7: Potential skyshine dose rates from an individual HHISO container with individual radionuclide activities at the limits determined by the 7.5 mSv h^{-1} surface dose rate criterion in the WAC [320]. All results given assume the receptor is 410 m away at a height of 5 m relative to top of the vault walls (at the field boundary south-east of the site).

Container	HHISO	**Surface dose rate**	7.5 mSv h^{-1}
Radionuclide	**Activity (GBq)**	**Skyshine dose rate (µSv h^{-1})**	
Container in top layer		**Edge of vault**	**Middle of vault**
^{60}Co	380	3.10×10^{-4}	1.17×10^{-3}
^{137}Cs	1,700	5.28×10^{-4}	1.33×10^{-3}
^{108m}Ag	640	6.01×10^{-4}	1.43×10^{-3}
^{226}Ra	820	6.03×10^{-4}	1.91×10^{-3}
Container shielded by one layer of containers		**Edge of vault**	**Middle of vault**
^{60}Co	380	1.21×10^{-11}	8.29×10^{-12}
^{137}Cs	1,700	6.86×10^{-14}	4.17×10^{-14}
^{108m}Ag	640	7.98×10^{-14}	4.93×10^{-14}
^{226}Ra	820	1.19×10^{-10}	9.00×10^{-11}

Table 7.8: Potential skyshine dose rates from an individual Demolition LLW bag with individual radionuclide activities at the limits determined by the 2 mSv hr^{-1} surface dose rate criterion in the WAC. All results given assume the receptor is 410 m away at a height of 5 m relative to top of the vault walls (at the field boundary south-east of the site).

Container	1 m^3 bag	**Surface dose rate**	2 mSv hr^{-1}
Radionuclide	**Activity (GBq)**	**Skyshine dose rate (µSv h^{-1})**	
Container in top layer		**Edge of vault**	**Middle of vault**
^{60}Co	0.5	7.10×10^{-7}	4.53×10^{-6}
^{137}Cs	2.3	1.32×10^{-6}	5.43×10^{-6}
^{108m}Ag	0.9	1.58×10^{-6}	6.08×10^{-6}
^{226}Ra	1.1	1.47×10^{-6}	7.61×10^{-6}
Container shielded by one layer of containers		**Edge of vault**	**Middle of vault**
^{60}Co	0.5	7.79×10^{-10}	9.07×10^{-10}
^{137}Cs	2.3	1.29×10^{-10}	1.17×10^{-10}
^{108m}Ag	0.9	1.26×10^{-10}	1.16×10^{-10}
^{226}Ra	1.1	1.30×10^{-9}	1.74×10^{-9}

Annual doses

527 All of the potential dose rates from skyshine presented above are hourly dose rates. In order to determine potential effective annual doses for comparison with regulatory guidance and criteria, it is necessary to make assumptions about patterns and times of occupancy at different locations.

528 Annual effective doses have been estimated for two patterns of typical behaviour representing a worker and a member of the public:

- Site worker – An individual spending 4 hours per day (960 h y^{-1}) outdoors around the facilities, with half of this time at 25 m and half at 100 m from the facilities.
- Farmer – An individual spending half of the year (4,383 hours) outdoors in the field between the site and the nearest house (410 m away). The occupancy time is based on the number of hours assumed for both the Livestock Farmer and Crofter RPs in the Run 5 PA [48].

529 Table 7.9 presents the annual effective dose estimates for LLW, LLW Pits and Demolition LLW based on the linearly scaled calculated dose rates and the occupancy assumptions described above. The results show that for members of the public (represented by the farmer), the potential annual doses from skyshine arising from a single vault would be small, and orders of magnitude below the regulatory dose constraint of 0.3 mSv per year (300 µSv y^{-1}) specified in the GRA and the 0.15 mSv per year dose constraint recommended by the HPA [68]. The potential

doses from skyshine to workers around the facilities during operations are higher than to members of the public but are still well within regulatory dose constraints.

Table 7.9: Potential annual doses from skyshine to two exposed groups derived via linearly scaled dose rates from those calculated in the 2010 assessment [320].

Behaviour	Potential annual dose from skyshine (µSv)		
	LLW	Pits	Demolition LLW
Site worker	21.30	41.05	12.79
Farmer	0.81	1.26	0.40

7.9 Radiological Impacts on Non-Human Biota and the Environment

GRA 6.3.70 and GRA 7.3.35

Requirement R9: Environmental radioactivity. The developer/operator should carry out an assessment to investigate the radiological effects of a disposal facility on the accessible environment both during the period of authorisation and afterwards with a view to showing that all aspects of the accessible environment are adequately protected.

GRA 6.3.74 Carry out an assessment and draw conclusions about the effects of a disposal facility on the accessible environment using the best available information at the time of the assessment. Provide this assessment as an integral part of the environmental safety case and update it as new information becomes available and when other parts of the case are updated. The extent and complexity of the assessment should be proportionate to the radiological hazard presented by the waste in the facility.

GRA 6.3.75 The assessment of effects on the accessible environment should include an assessment of effects after human intrusion, making the same human intrusion assumptions as when assessing the effects on people.

GRA 6.3.50 Present assessments of the radiation doses received by non-human organisms as a result of human intrusion into the facility and demonstrate that these are not at a level liable to cause significant harm to populations of such organisms.

530 The GRA recognises that there are no internationally recognised criteria for determining radiological protection of the environment, but notes research studies that propose such criteria. One such study is the ERICA Integrated Approach (Environmental Risk from Ionising Contaminants: Assessment and Management) [322]. The ERICA Integrated Approach was developed under the EC 6th Framework Programme and provides a comprehensive method to address the ecological effects of ionising radiation on organisms and ecosystems. The ERICA Integrated Approach is supported by the ERICA Tool [323], a software programme that can be used for assessing the radiological effects on biota.

531 An assessment of the potential impact of D3100 on non-human biota was undertaken using the Run 3 PA results for the planning application design [324]. This

assessment showed that the risk to any non-human organism from D3100 is negligible. The assessment has been undertaken for the as-built design using the concentrations of activity in the environment calculated using the Run 5 PA models [48]. Version 1.3.1.33 of the ERICA Tool has been used at the Tier 2 assessment level, which provides a more detailed and less conservative analysis than the Tier 1 level. Dose rates have been calculated to generic or "reference" organisms defined as representative for assessing the impacts of radiation within three different ecosystems: terrestrial, freshwater and marine. The calculated dose rates per reference organism for the respective environment have been compared against the dose rates that are specified in guidance on the Radioactive Contaminated Land (Scotland) Regulations 2007 as the levels above which significant harm might occur from lasting exposure (i.e. 40 μGy h^{-1} to terrestrial biota or plants and 400 μGy h^{-1} to aquatic biota or plants).

532 Within the terrestrial ecosystem, the ERICA Tool includes only a single environmental medium and, for the assessment reported here, radionuclide concentrations from the Farm Soil compartment of the PA model have been used to specify soil concentrations.

533 For the freshwater and marine ecosystems, the ERICA Tool allows environmental concentrations to be specified for either water or sediment. Therefore, aqueous radionuclide concentrations from the Surface Water compartment of the PA model have been used to specify water concentrations in a freshwater ecosystem, and aqueous radionuclide concentrations from the Marine Water compartment have been used to specify water concentrations for the marine ecosystem. For the freshwater ecosystem this is a particularly conservative approach; the water balance for each modelled compartment of the enhanced geosphere can discharge upward flowing groundwater to a generic "stream" compartment, which might include some contamination. In fact, this interflow tends to discharge at the foot of the enhanced geosphere on the coast, but it is cautiously assumed in the PA that this discharge is accessible and that livestock can drink it. It is unlikely that this discharge could be used by all of the freshwater reference organisms modelled in the ERICA Tool (e.g. fish, ducks) and, in any event, the impact would only be to a few individuals.

534 Distribution coefficients for the freshwater and marine ecosystems for input to ERICA have been sourced from the Run 5 PA [48, Tab.C9 & C11]. For all three ecosystems, ERICA requires specification of concentration ratios for each organism per radionuclide. The concentration ratios are the activity concentration in the biota whole body as a fraction of the activity concentration of filtered water for aquatic organisms, and as a fraction of the activity concentration in soil (or in air for certain radionuclides) for terrestrial organisms. For the majority of radionuclides, the concentration ratios supplied in the ERICA database within the Tool have been used – these are comparable to those specified by element for biota used as foodstuffs in the Run 5 PA [48, PVDF Run5_22]. However, data for a small number of elements, namely Mo, Pd, Sn, Sm and Ac, are not available within ERICA and were therefore sourced from the IAEA [306; 307], US Department of Energy [325], or, in the case of the terrestrial ecosystem, assumptions made based on the concentration ratios of similar radionuclides (Ag for Pd and Sn, Eu for Sm, Am for Ac) or for similar organisms (Mo, all values from [306] for one animal and one plant).

535 Dose rates were calculated for three different time periods for each reference organism: up to 1,000 years after 2020 CE, between 1,000 and 10,000 years, and post-10,000 years. For each of these, the maximum concentration for each radionuclide calculated in the PA was assumed regardless of its time of occurrence within the respective time period.

536 As well as the total dose rate per organism, ERICA outputs a risk quotient for each organism which is derived by division of the dose rate by the guidance value used for comparison. For Tier 2 assessments, two risk quotient values are calculated for every organism: the expected value risk quotient and the conservative risk quotient. An expected value risk quotient (and by implication also the conservative risk quotient) above one for any organism indicates that the assessment has exceeded the guidance value.

537 The total dose rates per reference organism, together with the expected value risk quotients, are presented in Table 7.10, Table 7.11 and Table 7.12 below for the marine, terrestrial and freshwater ecosystems respectively.

Table 7.10: Tier 2 ERICA assessment results for the marine ecosystem.

Reference Organism	Guidance value (μGy h^{-1})	Total dose rate per organism (μGy h^{-1})			Risk quotient (expected value)		
		Pre 1,000 years	1,000 to 10,000 years	Post 10,000 years	Pre 1,000 years	1,000 to 10,000 years	Post 10,000 years
Benthic fish	4.00E+02	1.94E-07	7.72E-07	1.28E-05	4.85E-10	1.93E-09	3.21E-08
Bird	4.00E+01	2.27E-07	8.95E-07	1.50E-05	5.67E-09	2.24E-08	3.74E-07
Crustacean	4.00E+02	1.30E-07	5.88E-07	1.16E-05	3.25E-10	1.47E-09	2.91E-08
Mammal	4.00E+01	2.22E-07	8.02E-07	1.48E-05	5.56E-09	2.21E-08	3.70E-07
Mollusc - bivalve	4.00E+02	9.50E-08	4.11E-07	8.38E-06	2.38E-10	1.03E-09	2.09E-08
Pelagic fish	4.00E+02	1.83E-07	7.09E-07	1.21E-05	4.57E-10	1.77E-09	3.02E-08
Phytoplankton	4.00E+02	1.52E-06	7.20E-06	1.84E-04	3.80E-09	1.80E-08	4.60E-07
Reptile	4.00E+01	2.22E-07	8.82E-07	1.48E-05	5.56E-09	2.21E-08	3.70E-07
Vascular plant	4.00E+02	1.29E-07	6.53E-07	2.46E-05	3.22E-10	1.63E-09	6.16E-08
Zooplankton	4.00E+02	1.16E-07	4.51E-07	8.15E-06	2.91E-10	1.13E-09	2.04E-08
Macroalgae	4.00E+02	1.32E-07	6.15E-07	1.48E-05	3.31E-10	1.54E-09	3.69E-08
Polychaete worm	4.00E+02	2.23E-07	1.24E-06	7.88E-05	5.56E-10	3.10E-09	1.97E-07
Sea anemones & True coral	4.00E+02	2.02E-07	1.16E-06	7.80E-05	5.06E-10	2.89E-09	1.95E-07

Table 7.11: Tier 2 ERICA assessment results for the terrestrial ecosystem.

Reference Organism	Screening value (µGy h^{-1})	Total dose rate per organism (µGy h^{-1})			Risk quotient (expected value)		
		Pre 1,000 years	1,000 to 10,000 years	Post 10,000 years	Pre 1,000 years	1,000 to 10,000 years	Post 10,000 years
Bird	4.00E+01	6.91E-05	1.49E-04	1.32E-04	1.73E-06	3.73E-06	3.29E-06
Reptile	4.00E+01	6.96E-05	1.62E-04	1.65E-04	1.74E-06	4.04E-06	4.13E-06
Amphibian	4.00E+01	6.73E-05	1.59E-04	1.60E-04	1.68E-06	3.98E-06	4.00E-06
Annelid	4.00E+01	2.33E-05	9.71E-05	1.49E-04	5.83E-07	2.43E-06	3.74E-06
Arthropod - detritivorous	4.00E+01	2.33E-05	9.67E-05	1.47E-04	5.84E-07	2.42E-06	3.67E-06
Flying insects	4.00E+01	2.31E-05	9.13E-05	1.36E-04	5.78E-07	2.28E-06	3.39E-06
Grasses & Herbs	4.00E+02	5.23E-05	3.04E-04	5.27E-04	1.31E-07	7.61E-07	1.32E-06
Lichen & Bryophytes	4.00E+02	8.05E-05	1.03E-03	2.07E-03	2.01E-07	2.58E-06	5.17E-06
Mammal - large	4.00E+01	6.94E-05	1.57E-04	1.56E-04	1.73E-06	3.93E-06	3.90E-06
Mammal - small-burrowing	4.00E+01	6.96E-05	1.62E-04	1.66E-04	1.74E-06	4.05E-06	4.15E-06
Mollusc - gastropod	4.00E+01	2.33E-05	9.65E-05	1.54E-04	5.84E-07	2.41E-06	3.85E-06
Shrub	4.00E+02	5.99E-05	5.04E-04	9.33E-04	1.50E-07	1.26E-06	2.33E-06
Tree	4.00E+02	6.57E-05	1.11E-04	5.84E-05	1.64E-07	2.78E-07	1.46E-07

Table 7.12: Tier 2 ERICA assessment results for the freshwater ecosystem. Red highlighted cells show a risk quotient greater than one.

Reference Organism	Screening value (µGy h^{-1})	Total dose rate per organism (µGy h^{-1})			Risk quotient (expected value)		
		Pre 1,000 years	1,000 to 10,000 years	Post 10,000 years	Pre 1,000 years	1,000 to 10,000 years	Post 10,000 years
Amphibian	4.00E+01	2.34E+01	3.23E+01	2.21E+02	5.85E-01	8.07E-01	5.53E+00
Benthic fish	4.00E+02	9.65E-01	1.38E+00	8.49E+00	2.41E-03	3.46E-03	2.24E-02
Bird	4.00E+01	2.48E+01	3.42E+01	2.34E+02	6.21E-01	8.56E-01	5.84E+00
Crustacean	4.00E+02	1.31E+00	1.89E+00	1.43E+01	3.28E-03	4.72E-03	3.59E-02
Insect larvae	4.00E+02	9.20E+01	1.27E+02	8.68E+02	2.30E-01	3.17E-01	2.17E+00
Mammal	4.00E+01	1.67E-01	3.20E-01	2.62E+00	4.18E-03	8.01E-03	6.56E-02
Mollusc - bivalve	4.00E+02	9.01E+01	1.24E+02	8.58E+02	2.25E-01	3.11E-01	2.15E+00
Mollusc - gastropod	4.00E+02	9.01E+01	1.24E+02	8.58E+02	2.25E-01	3.11E-01	2.15E+00
Pelagic fish	4.00E+02	8.73E-01	1.26E+00	8.05E+00	2.18E-03	3.14E-03	2.01E-02

Reference Organism	Screening value (µGy h⁻¹)	Total dose rate per organism (µGy h⁻¹)			Risk quotient (expected value)		
		Pre 1,000 years	1,000 to 10,000 years	Post 10,000 years	Pre 1,000 years	1,000 to 10,000 years	Post 10,000 years
Phytoplankton	4.00E+02	2.09E+00	2.95E+00	2.24E+01	5.23E-03	7.37E-03	5.60E-02
Reptile	4.00E+01	3.17E+00	4.46E+00	3.08E+01	7.93E-02	1.11E-01	7.69E-01
Vascular plant	4.00E+02	4.29E+00	6.15E+00	5.66E+01	1.07E-02	1.54E-02	1.41E-01
Zooplankton	4.00E+02	9.17E+01	1.26E+02	8.65E+02	2.29E-01	3.16E-01	2.16E+00

538 The assessment shows that the low concentrations of radioactivity in the environment calculated to result from releases from D3100 gives dose rates for all reference organisms across the marine and terrestrial environments below the guidance levels. However, for the freshwater ecosystem, the calculated dose rates exceed the guidance values for the post-10,000 year time period for six reference organisms: amphibians, birds, insect larvae, mollusc – bivalve, mollusc – gastropod, and zooplankton. Further, the results show that there is a greater than 5% probability of exceeding the guidance value for reptiles as well, assuming the risk quotient distribution is exponential. For the pre-1,000 years and 1,000 to 10,000 year time periods for the freshwater ecosystem, none of the dose rates exceed the guidance values, though there is a greater than 5% probability of exceeding the guidance value for amphibians and birds.

539 While some of the calculated risk quotients for the freshwater ecosystem exceed one, the results of the ERICA assessment are considered acceptable. There are several additional considerations to take into account:

- Use of radionuclide concentrations from the Surface Water compartment of the PA model is very pessimistic as the surface water ditches close to D3100 are not likely to be sufficient to support a freshwater ecosystem and the reference organisms highlighted as of concern are in reality unlikely to be present.

- The organisms in the ditches close to D3100 are common in the northern Scotland environment, and any impact of D3100 on a local population of the organisms will not be significant in terms of the general viability of any species.

- Calculation of the radionuclide concentrations in the Surface Water compartment in the PA are simplistic and are not reflective of the likely real situation. For the purposes of the PA calculation, where the main issue is the overall release rate of radioactivity first to the surface water and then over the cliffs into the sea, all of the water flowing from the soil into the generic "stream" is modelled as flowing into one compartment with a nominal cross-section of 1 m^2. In reality, flow will be into a network of ditches with a much greater aggregate cross-section and the consequent radionuclide concentrations experienced by organisms, if present in the ditches, will be much lower.

- One of the main contributors to the dose rates calculated in the ERICA Tool for the freshwater ecosystem is ^{226}Ra, which is also a naturally-occurring radionuclide. Despite the bounding approach, the concentrations calculated in the PA are similar to background concentrations of natural radioactivity at Dounreay [235, Tab.4.5]. This is illustrated in Table 7.13. Further, the Environmental Media Concentration Limit (EMCL) in the ERICA Tool is the concentration at which the risk quotient for the most limiting reference organism exceeds one [322]. The EMCL for ^{226}Ra is considerably below the World Health Organisation guidelines for drinking water [326, Tab.2] and is lower than the background concentration for many surface freshwaters [327], suggesting that organisms can actually receive a higher dose from this radionuclide than the generic guidance value (40 µGy h^{-1} for an amphibian) without experiencing a deleterious effect.

Table 7.13: Radionuclide concentration in the PA Surface Water compartment compared to naturally-occurring concentrations from various sources.

Radionuclide	**D3100 Baseline measured value (Bq L^{-1}) [235]**	**Peak PA Concentration (Bq L^{-1}) [48]**			**Other values**			
		Pre 1,000 years	**1,000 to 10,000 years**	**Post 10,000 years**	**ERICA EMCL (Bq L^{-1}) [322]**	**IAEA Global Surface Waters [327, §3.4]**	**BGS UK Ground-water [328]**	**WHO Drinking Water Guide-lines [326]**
^{226}Ra	<3.0	0.03	0.04	0.3	0.01	0.0005 – 0.022 (but up to 0.3)	0.001 – 0.4	1
^{234}U	-	0.0004	0.008	0.5	5.1	-	-	1
^{210}Pb	<2.6	0.002	0.002	0.02	47	-	-	0.1
Gross Alpha Activity	0.3	0.03	0.04	0.1	-	-	-	0.5
Gross Beta Activity	0.5	0.13	0.11	0.05	-	-	-	1

540 Concentrations in soils following human intrusion could be slightly higher than shown in Figure 7.13, but the calculated doses to reference organisms in the terrestrial environment following inadvertent human intrusion remain below the dose rates specified in the guidance on the Radioactive Contaminated Land (Scotland) Regulations 2007 (i.e. 40 µGy h^{-1}). The highest risk quotient calculated using the peak soil concentrations following human intrusion is 5.6×10^{-3} (conservative value of 1.7×10^{-2}) to a large mammal. Therefore, the risk to any non-human organism from D3100 following inadvertent human intrusion is negligible.

7.10 Impacts from Non-Radioactive Hazardous Materials

GRA 6.4.1 and GRA 7.3.36 **Requirement R10: Protection against non-radiological hazards.** The developer/operator of a disposal facility for solid radioactive waste should demonstrate that the disposal system provides adequate protection against non-radiological hazards.

GRA 6.4.2 A level of protection should be provided against non-radiological hazards that is no less stringent than would be provided if national standards for disposing of waste that presents non-radiological hazards but not a radiological hazard were applied.

GRA 6.4.5 The environmental safety case should demonstrate that adequate protection against non-radiological hazards is achieved, using methods and approaches suited to the nature and proportionate to the magnitude of the hazards and suited to the characteristics of the disposal system.

541 An inventory of potentially hazardous components of the Dounreay LLW has been compiled by DSRL and is discussed in paragraphs 99-103 and presented in Table 4.5. A position paper on the management of non-radioactive hazards (NoRaH) in D3100 was prepared by DSRL in 2010 to support the original application [181], and has subsequently been revised to account for operational experience gained in the last few years [53]. The low inventory of hazardous components and high standard of engineering in the disposal facilities are considered to provide a level of long-term protection of the environment against non-radiological hazards that is no less stringent than that provided by national standards for disposing of hazardous waste, as required by the GRA [19, ¶6.4.2]. The D3100 disposal facilities are at least equivalent to a hazardous waste facility in the following key areas [53, §4]:

- *Engineering design and performance.* The engineering of D3100 is based on the construction of high-quality concrete vaults, with the design incorporating multiple barriers and making extensive use of concrete. Hazardous waste facilities, by contrast, typically rely on a single barrier, made using clay, for containment.

  The facilities have been designed such that no releases of contaminants are expected during normal operations before they are closed. DSRL has optimised the design and build of the vaults in order to demonstrate that the vaults have been and can be constructed to achieve containment for at least 60 years (typically required for hazardous landfills). Indeed, simplified and conservative calculations indicate that it would take at least 200 years to saturate the vaults. A design requirement was specified that all of the bases and walls of the vaults (both LLW vaults and Demolition LLW vaults) will be constructed of 0.5 m minimum-thick concrete with suitably low permeability ($<1.0 \times 10^{-10}$ m s^{-1}); this satisfies an engineering design Condition in the Permit [14, Condition 7.4]. The Demolition LLW vaults are designed to have thicker walls than the LLW vaults (1.1 m) to provide additional structural strength, as the wastes within are loose and will not be grouted. The design hydraulic conductivities and thicknesses of the D3100 vaults are considered to be equivalent to the requirements for a hazardous waste facility under the landfill regulations.

Few non-radiological hazardous contaminants are anticipated to be present in the LLW in any significant quantities (i.e. at concentrations >0.5 wt%). However, it is expected that all of the NoRaH contaminants will be rendered immobile for the first few hundred years after closure by the LLW conditioning and the packaging. During this period, an appropriate level of protection of the water environment against NoRaH is expected to be provided by the containment function of the facilities. This will be due to the presence of several engineered barriers impeding water ingress to the LLW, the low leachability of the cement-grouted wasteform, and the likely retardation of contaminants inside a LLW vault. As the Demolition LLW vaults are to be constructed to the same or higher standard of water-tightness as the LLW vaults, containment of NoRaH contaminants in a Demolition LLW vault is expected over a timescale similar to that for a LLW vault. In addition, the hazardous component of Demolition LLW is substantially smaller than the limited amount that is associated with the LLW.

The above design aspects contribute to the overall performance of the facilities in terms of release and migration of NoRaH, with the low permeability of the vault structures being the most significant. The cement-grouted waste and the chemical barrier functions of the engineered barrier system (backfill and walls) add significant extra lines of defence. Together, the waste conditioning, waste packaging and construction protocols for D3100 provide levels of protection against NoRaH that will be as effective as those achieved by a modern hazardous waste facility. On this basis, D3100 is considered to at least meet, if not exceed, the relevant "*nationally acceptable standards*" of performance for the protection of people and the environment against non-radiological hazards.

- *Waste characterisation.* Under the landfill regulations, there are requirements for identification, treatment, acceptance, disposal, monitoring and assessment of hazardous wastes in order to be protective of human health and the environment. Acceptance of wastes into D3100 is contingent on waste consignors (the Dounreay site) demonstrating that the wastes are compliant with the D3100 WA Rules for the facilities, which are required to ensure that waste disposals comply with assumptions that underpin this ESC (and thus the EASR 18 Permit [14]), the D3100 Nuclear Safety Case [55] and the D3100 Planning Application [16]. As discussed in Section 4.4, the WA Rules are implemented on the Dounreay site via the site's CfA [112], to which the waste consignors package their wastes.

  On the Dounreay nuclear licensed site, responsibility for identifying and documenting hazardous materials in LLW belongs with the site waste consignors, to ensure that the LLW can be handled and transported safely. The Dounreay Waste Manual [107] ensures that control and management procedures are in place to ensure that LLW complies with the current site LLW CfA [112]. DSRL's management arrangements for conventional hazardous materials follow a similar tiered structure, including an associated set of CfA ('Radiologically Clean Waste Conditions for Acceptance') [329]. WCTP audits [128] will be used by D3100 to ensure and demonstrate this alignment of the D3100 WA Rules and the Dounreay site LLW CfA. In this way, the site procedures for managing LLW containing NoRaH are consistent with D3100 requirements. The consignment documentation reviewed by D3100 in the waste acceptance process records the NoRaH content of a waste package, and this information is stored in the Dounreay DMS.

- *Management Plans.* Landfill regulations require that management plans are in place to demonstrate how hazards are to be managed (e.g. to control leachate or any gas generated). The design and content of D3100 does not require a leachate collection and treatment system, nor a landfill gas management system (no leachate is expected to arise, and generated gas volumes are expected to be low due to limits on biodegradable wastes). There is therefore no applicable comparison to be made with a landfill for hazardous waste.

  However, operations in D3100 are conducted according to the Operational Management Plan (OMP) [116], as required by the EASR Permit. Drainage systems and event response systems for D3100 are in place to prevent hazardous substances from entering the water environment in the event of a flood, with documented recovery strategies and operating instructions.

  Quality assurance procedures are in place to ensure that a waste package complies with the WA Rules, that there is safe transport of the package to the relevant vault, and that the disposal operation is carried out in a safe and approved manner, in accord with the Load Management Plan [127]. Appropriate inspection checks of the emplaced waste packages will be performed up to closure of the vault. A Records Management Plan has been developed [330]; records are kept confirming compliance with the WA Rules and the Permit, and, by implication, with nationally acceptable standards for disposal of hazardous waste. Suitable waste disposal records will be arranged to be kept for the long term.

- *Monitoring*. Landfill monitoring is guided by the performance standards expected during the assessment period of concern, which includes operations and a post-closure institutional control period for D3100. As discussed in Section 10, an Environmental Monitoring Programme (EMP) is in place for D3100 that sets out the environmental monitoring required to maintain compliance with the EASR 18 Permit and the ESC during the operational phase of the facilities. In order to provide reassurance that post-closure performance standards will be met, the EMP will be updated to provide appropriate monitoring during the period of institutional control following facility closure.

542 Therefore, the level of protection offered by D3100 is equivalent to, if not exceeding, that required for hazardous waste facilities, thereby meeting Requirement R10 of the GRA [19]. The overall strategy behind D3100 provides for long-term containment of the hazardous contaminants and protection of the environment.

543 As discussed in Section 4.3.4, only a few non-radioactive hazardous contaminants, mainly lead, copper and asbestos, are anticipated to be present in the LLW in any significant quantity, and these contaminants are present in inert forms or will be rendered inert by the waste conditioning. Consistent with international

recommendations (e.g. [331]), both DSRL, via the WA Rules, and SEPA, via the Authorised WAC in the Permit, impose conditions and limitations to control the disposal of hazardous contaminants. These controls are implemented on the Dounreay site by DSRL through the CfA applied as part of the DSRL Waste Management Process.

544 The 2020 NoRaH report [53, §5] identifies learning obtained from operating D3100 and reviews the WA Rules and D3100 Permit Conditions that relate to NoRaH. The review noted three key points when considering the safety implications of wastes disposed of in D3100 [53, §5]:

- The D3100 Permit holder cannot guarantee the content of waste packages; the D3100 Compliance Team can only assure that waste acceptance criteria are being met based on the evidence supplied by the consignor. The ability to guarantee the content of the waste package rests with the waste consignor during generation, characterisation, treatment and packaging.
- Post-closure, the long-term environmental safety of the facilities with respect to non-radiological hazards is ensured predominantly by the engineering and construction of the vaults (as discussed above).
- Environmental safety requirements for the vaults during operations differ depending on the form of the waste. Emplacement and stacking operations for containerised, grouted wastes in the LLW vault involve less potential interaction with the waste material itself than those for Demolition LLW (and those anticipated for non-containerised LLW).

  There is no greater risk to environmental safety from stacking operations for grouted HHISOs than from equivalent handling and transport operations within the nuclear licensed site boundary. On the licensed site, the responsibility for making sure that wastes are safe to handle and transport – including from a non-radiological hazard perspective – lies with the waste consignors, and hazards must be identified and dealt with appropriately. This includes consideration of accidents (e.g. dropping a container) and whether there is the potential for release of hazardous material and impact on the environment. Clearly, once the waste in a HHISO is grouted, before it leaves the Dounreay site for D3100, the potential for hazardous material release following an accident is negligible. Therefore, it can be argued that grouted, containerised waste that is safe to handle and transport within the bounds of the nuclear licensed site is safe from an operational perspective within D3100, such that there is no need to undertake additional actions to stabilise hazardous materials beyond any methods that have already been employed to render the waste safe for movement on and around the Dounreay licensed site.

  Contrastingly, operations and transport on the nuclear licensed site do not provide a bounding safety envelope for emplacement of Demolition LLW packages[31]. Transport and handling operations up to the point of emplacement are no different from those on the Dounreay site. However, during vault operations, a thin layer of granular material is used to infill voids around the Demolition LLW to minimise settlement of the waste and to give safe operational access (a firm and even working surface) over the top of already-emplaced waste. A thin cover layer of granular material is placed between the waste layers. A core assumption that underpins continued operations on top of the emplaced waste is that Demolition LLW may only contain low amounts of potentially hazardous materials buried within large volumes of inert materials, thereby minimising the risk of operator exposure [55, ¶129]. Thus, the primary function of the granular material is to enhance the engineered performance of the facilities and provide a safe running surface; there is no requirement for a minimum thickness of material to manage risks from NoRaH. Accounting for this, and that standard practice at a hazardous waste landfill site is to use 1 m of clean cover material between layers of hazardous waste, suggests that revisions to the D3100 Hazard Analyses would be required in order to safely emplace Demolition LLW that includes more than trace amounts of NoRaH materials, and that there would be an associated reduction in the amount of waste that could be accommodated within the D3130 vault due to the need to emplace additional clean cover material.

545 DSRL considers that these key arguments are not fully reflected by the extant Permit conditions and WA Rules. As a result, waste management and acceptance for disposal are not perceived to be clear or proportionate to the hazard presented, placing unnecessary burdens on both the D3100 Compliance Team and site waste consignors. Therefore, the NoRaH report [53] proposes simplification and revision of the relevant Authorised WAC and WA Rules [131] that pertain to management or control of NoRaH. It is proposed that the Authorised WAC for NoRaH are replaced with an overarching holistic condition which requires that D3100 assures that any properties that would be considered hazardous if the waste was not radioactive are declared by the consignor, that all such materials have been made safe for transport and disposal operations, and that the method(s) used are justified by the consignor. This proposed change addresses the issue with obsolete terminology within the extant Permit conditions and future-proofs the requirements against future changes to NoRaH legislation and guidance. It is recognised that the proposed condition appears more generic than the current list of individual requirements. However, the intent of the change is that it will drive the consignor to consider hazards more holistically and in line with conventional waste legislation and guidance, resulting in better characterisation, management and risk reduction of all potential hazards in the waste, rather than solely those listed in the Permit.

31 Noting that, as discussed in Section 4.3.4, the nature of Demolition LLW is such that it is unlikely to have high levels of non-radiological hazards.

546 The NoRaH-related Rules in WA Rules 2020 [133] (see Section 4.4 and Appendix A) have been revised for consistency with the proposed Authorised WAC for NoRaH, as follows:

- Hazardous materials must be excluded from non-containerised LLW and Demolition LLW unless their inclusion has been approved through an exception process.
- Hazardous materials must be prepared and made safe for transport and operations before the waste package can be accepted for disposal.
- The hazardous content of raw waste must be declared by the waste consignor. The method of preparing the hazardous content so that it is safe must also be declared, even where the method is grouting of the package in the D2179 grout plant.

7.11 Criticality Safety Assessment

GRA 6.4.21	In design and construction, take into account a number of effects that may arise from properties of the waste, including: - … - criticality through concentration of fissile nuclides (for near surface facilities, this can probably be dealt with by a simple analysis).

547 In addition to limits on the activity of radionuclides in D3100, limits on the fissile mass in waste packages are also imposed to meet criticality safety requirements. As presented in Section 4.3.5, the LLW fissile inventory is dominated by ^{235}U, with only a small amount of ^{239}Pu present. However, in general, LLW contains low concentrations of fissile material distributed throughout the waste volume and as such the waste does not present a criticality hazard. This argument is supported by the fact that the average fissile radionuclide concentration in the waste is orders of magnitude below that required for criticality even under the most ideal conditions; the LLW best estimate ^{235}U fissile equivalent concentration is 2.2×10^{-3} kg m^{-3} whilst the critical infinite sea concentration (i.e. the minimum concentration required for criticality) in saturated grout is ~9 kg ^{235}U m^{-3}. Therefore, fissile material would need to be concentrated substantially for criticality to be possible.

548 The fissile mass limits on the waste for consignment to D3100 (WA Rule 6) are based on the criticality safety assessment (CSA) for D3100. The 2011 CSA [332], which supported the original authorisation application, has been reviewed and revised in 2020 [52] to take account of experience gained from operating the facilities, reduce conservatism in the analysis without compromising criticality safety, improve clarity, and account for the revised inventory data.

549 The criticality safety case for the operational period of the D3100 disposal facilities demonstrates that the derived fissile mass limits are conservative and that criticality is not credible. However, it is also necessary to demonstrate that criticality will not occur after closure of the D3100 disposal facilities. Such a safety assessment has to consider the potential for a critical mass or concentration of fissile material to accumulate in the long term under disposal conditions.

550 Based on the analysis presented in the CSA [52], it is judged that criticality after closure of the D3100 disposal facilities is not credible, which is ensured by application of package fissile mass limits. This judgment is based on the following considerations:

- The total masses of all of the fissile isotopes, except ^{235}U and ^{239}Pu, in all of the D3100 vaults will be less than the minimum required for criticality under the most pessimistic conditions conceivable.
- Waste package fissile material limits are based on highly pessimistic assumptions that introduce large criticality safety margins.
- Fissile material will be widely distributed in many waste packages throughout the disposal vaults and will be present in unfavourable geometries for criticality.
- Fissile isotopes will be mixed with much larger quantities of neutron absorbers in the waste packages that will further limit the potential for criticality. For example, fissile material will be mixed with steel and cementitious grout in many waste packages; such waste packages will thus include neutron absorbing iron.
- The wasteform and containers will prevent mobilisation of fissile material in the short term after disposal.
- In the long term, any credible accumulation or concentration of ^{235}U or ^{239}Pu will not be sufficient to result in criticality.

551 The 2020 CSA has derived revised fissile mass limits for waste packages, as summarised below, which are proposed to replace the relevant Authorised WAC and are included in the 2020 WA Rules [133] (see Appendix A):

- Each LLW HHISO that contains only compacted and/or uncompacted 200 litre drums is limited to 600 g (^{235}U + 1.7 ^{239}Pu)[32], with a limit of 20 g (^{235}U + 1.7 ^{239}Pu) and 100 g beryllium per puck/drum.
- Each LLW HHISO**,** containing any mixture of solid LLW with no restriction on its physical form, may contain 90-115 g (^{235}U + 1.7 ^{239}Pu), depending on the mass of beryllium and graphite present.
- Non-containerised LLW items must meet the mixed containerised LLW limits applied *pro rata* per 20 m^3 of waste.
- Demolition LLW is limited to 6 g ^{235}U per 1 m^3 of waste[33].

552 The fissile limits have been derived on the assumption that every container in the vaults could be loaded to the same (maximum) fissile mass. In reality, the fissile material content of most containers would be much less. Indeed, if every one of the 1,960 HHISO containers that can be placed in vault LLW-1 were to contain the

32 (^{235}U + 1.7 ^{239}Pu) means the mass of ^{235}U plus the mass of ^{239}Pu multiplied by 1.7.

33 The ^{239}Pu content of Demolition LLW is negligible so a criticality control does not need to be applied.

maximum permitted fissile mass, then the total fissile mass in the vault would be more than five times the best estimate for the ^{235}U content in the entire inventory. Therefore, the assumed distribution of fissile material in the criticality safety analysis is cautious. Also, if the maximum fissile mass is distributed uniformly throughout a HHISO, then it would be at a concentration that is more than 300 times lower than the critical infinite sea concentration in saturated grout. Therefore, there are large safety margins in the D3100 criticality safety controls for the operational and post-closure periods.

553 The CSA demonstrates that, although limited local accumulations of fissile material might occur during the D3100 post-closure period, the applied criticality safety controls and the design of the D3100 disposal facilities ensure that occurrence of an accumulation large enough to produce a neutron chain reaction is not credible. This assessment supports the FEP analysis for the PA, which screened out the nuclear criticality FEP (FEP 4.1.14 in Table 7.1) from the PA on the basis of low probability of occurrence.

554 The derived controls are expected to be met by the majority of wastes accepted for disposal in the D3100 vaults. However, there may be occasional non-standard packages or items that cannot meet these requirements, but it is likely to be possible to make a BPM case for their disposal in D3100 using knowledge of the item requiring disposal. The two options for such items, which may be applied in combination, are to adopt selected emplacement and load management controls (this will generally be applicable for packages with fissile contents slightly above the standard fissile mass limits) and/or to produce a package-specific CSA. The final element of the revised criticality safety WA Rule states that exceptions to the limits for containerised LLW may be agreed through an exception process (see Appendix A).

7.12 Collective Dose

GRA 6.3.69	Calculate collective doses and ‘group’ doses only for times where they can be a useful discriminator between different waste management options. This is likely to be of the order of several hundred years post-closure but the exact length of time will be dependent on the waste disposed of and type of facility and is not likely to be very long term in view of the large uncertainties.

555 Calculations of collective dose have not been undertaken for the D3100 project. The consideration of collective radiological impacts is discussed in the GRA [19, ¶6.3.68 and 6.3.69], but only in the context of its use as a potential discriminator between different waste management options. No such instance has been identified in the options analyses and optimisation studies conducted for D3100 to date. DSRL’s approach is consistent with the views of ICRP [66] that optimisation is the most appropriate means of achieving protection of the public. ICRP recognises the uncertainties involved in assessing collective dose at future times. Thus, instead of using collective dose in optimisation decisions, ICRP recommends that annual individual dose to a critical group (normal exposures) or annual individual risk (potential exposures) be used in comparisons of radiological detriment from radioactive waste disposal.

7.13 Future Development of the Quantitative Assessment

556 The D3100 project PA will likely undergo future iterations in tandem with future issues of the ESC (Figure 2.1). The need for, and scope of, each iteration will depend on developments in site characterisation, inventory estimation, design, PA validation, and national and international PA of other radioactive waste disposal facilities. The Run 2 PA was peer reviewed [333; 334] and reviewed on behalf of SEPA [277]. Development of the Run 3 PA took these review comments into account. The Run 4 and 5 PAs refined the Run 3 PA models to account, in particular, for design and inventory changes. The Run 5 PA modelling platform will continue to be used to assist in the development of the D3100 project.

557 The following set of tasks will be undertaken for each iteration of the PA:

- review of the inventory;
- review of the Dounreay LLW FEP catalogue;
- review of the scenarios and modelling approach;
- review of RPs;
- updating of modelling assumptions and conceptual models, including analysis of alternative conceptual models;
- updating of the PA parameter database;
- further PA model verification as necessary;
- conduct PA calculations;
- documentation; and
- PA management.

558 One possible additional future task relates to reimplementation of the existing GoldSim models. Since the original development of the PA models in GoldSim for Run 2 the GoldSim software package has expanded significantly. While the older modelling approaches are still valid, the model could be simplified/enhanced to take advantage of new features implemented in more recent versions of GoldSim. In addition, the groundwater pathway and human intrusion models could be combined within a single GoldSim model to assist with future updates.

559 In between full iterations of the D3100 project PA, the PA models may be used for particular applications, such as optimisation analyses and/or assessment of non-radiological impacts.

FP.8	Maintain PA capability and periodically review the need for PA updates.

8 SUM OF FRACTIONS

560 The radionuclide activity disposal limits within the Permit [14, Sch.2] are based on the 2009 inventory best estimates presented in ESC 2010 Issue 1 [28]. However, the way these limits were selected for inclusion in the Permit did not fully account for uncertainties in the inventory estimates, especially those associated with radionuclides that are not significant in respect of their contribution to calculated post-closure risks. Further, the 2009 inventory estimates have been updated (see Section 4.3) and the limits in the Permit no longer tally with the best expectations of the Dounreay decommissioning programme. Hence, DSRL established a programme of work to review [335] the approach to setting and managing radionuclide activity levels, which has led to the current application to SEPA to vary the existing D3100 Permit to change waste acceptance procedures to use a risk-based sum of fractions (SoF) approach. This SoF approach will allow for control of disposals that is consistent with the ESC while providing for greater flexibility during waste acceptance to account for inventory uncertainty.

561 This section summarises the results of the review and sets out the proposed way forward:

- Section 8.1 summarises the current predicted best-estimate inventory approach and the challenges associated with it.
- Section 8.2 reviews the two alternative approaches that have been considered, a predicted inventory approach that includes a margin for uncertainty and a SoF approach.
- Section 8.3 summarises how the preferred option, a SoF approach, has been implemented using the Run 5 PA models to derive radionuclide control levels for managing waste acceptance in the future.
- Section 8.4 sets out the changes to be implemented in the D3100 waste acceptance and compliance process if the proposed SoF approach is accepted by SEPA.

8.1 Current Position (Predicted Best-Estimate Inventory Approach)

562 For the Run 3 PA, the radionuclides in the projected LLW inventory in DRWI 2009 were screened against the concentration for each radionuclide in the legal definition of radioactive waste (the Out-of-Scope values defined in extant legislation at the time of the Run 3 PA). Those radionuclides with a concentration in the waste within a factor of at least one hundredth of the lower limit of the definition of radioactive waste, and any radionuclides in associated decay chains, were considered as potentially significant and modelled in the PA – this, therefore, gave the list of radionuclides specified in the current Permit. However, having then conducted the D3100 PA calculations, only a subset of these radionuclides proved to be significant contributors to the total calculated dose.

563 The main challenge of the current approach is that the limits derive directly from predicted inventory best estimates that themselves have large associated volumetric

and radionuclide uncertainties. The key uncertainties that impact this predicted inventory approach are:

- **Waste characterisation.** The degree to which waste is characterised introduces uncertainty around declared radionuclide activities. For example, it may not be feasible to properly characterise a waste stream until the decommissioning or demolition of a facility has begun. Even if some characterisation has been undertaken, the uncertainties will only be reduced when the facility is demolished and the waste arisen and packaged. This source of uncertainty applies to the majority of waste planned for disposal in D3100.
- **Waste fingerprints.** Radiological fingerprints are typically used to infer radionuclide activities for a specific waste stream and thus simplify (and reduce costs associated with) the waste characterisation process. This simplification introduces additional uncertainties, such as the frequency with which the fingerprint is decayed, its applicability to the entire waste volume (i.e. variability in the large volumes of decommissioning wastes over which the fingerprint is equally applied), uncertainties in the waste assay process, uncertainties on ratios between alpha and non-alpha activities, and measurement uncertainty in the key radionuclides to which the fingerprint is scaled.
- **Opportunities and plans.** Planning assumptions have been made regarding disposal routes for each waste stream, but opportunities may be identified in the future as better characterisation information becomes available. For example, wastes near the ILW/LLW boundary may be disposable in D3100 if they can be demonstrated to be LLW through additional assessment and characterisation. Alternatively, wastes currently allocated for disposal in D3100 may be diverted to recycle/reuse routes, or on-site / *in situ* disposal may be considered instead. This necessitates the use of assumptions around the relative proportions of waste streams that may require disposal in the D3100 facilities, which in turn impacts the inventory assumed in the PA and ESC.
- **Trace inventories.** A number of activities in the original inventory estimate reflect prediction of radionuclides at ‘trace’ levels. Some of these trace radionuclides were not directly screened in during the PA calculations, but were included because they arose in decay chains or in LLW but not Demolition LLW. Inclusion of these nuclides in the Permit has resulted in disproportionately low limits for radionuclides that have little impact on the calculated risk (as is the case for ^{152}Eu and ^{242}Pu). This does not apply a risk-based approach to control of disposals and hinders flexibility.

564 Issues encountered during the early stages of disposals to D3100 have demonstrated the challenge – namely, that accurate inventory predictions cannot be produced due to the nature of the waste characterisation and forecasting processes, and that when these estimates are later revised, a formal variation to the D3100 Permit will likely be required in order to enable continuing operations. It is possible that if the limits had been restricted to a smaller number of key radionuclides that

have the greatest safety and environmental consequences, compliance, and demonstration of compliance, may have been less problematic. Tying the authorised activity limits directly to the predicted inventory estimates provides a clear link, but takes no account of the uncertainty in that inventory estimate or whether the radionuclides are significant contributors to calculated post-closure risks. Therefore, it has been determined that an alternative approach to controlling the disposal inventory should be implemented [335].

8.2 Alternative Approaches

565 The EA [336] discusses two main approaches used internationally for setting authorisation conditions on the basis of a disposal facility's post-closure safety case: set conditions directly on PA assumptions (e.g. a fixed inventory); and/or set conditions via an optimisation process. Thus, two alternative approaches to the current use of an estimated disposal inventory to set activity levels for waste management were considered [335]:

- levels are set to encompass estimated waste inventory uncertainty and identified inventory scenarios for a reduced number of radionuclides that have the greatest impact on safety and the environment; or
- a SoF approach is used whereby radionuclide activity levels are derived, independent of each other, that meet regulatory performance measures based on assessment of the performance of the facility and radionuclide properties – the levels are then combined to reflect any given inventory in a SoF calculation.

8.2.1 Predicted inventory that caters for future uncertainty

566 The predicted inventory for D3100 is uncertain, not least because it relies on estimates of the activity present in facilities that have not yet been decommissioned or fully characterised. Therefore, an obvious alternative to the approach currently implemented is to build on this by making use of the upper estimate of inventory activities, rather than the best estimate, and by considering a range of potential inventory scenarios (see Section 4.3). Restricting the radionuclides included in the analysis to the smallest practicable number of key contributors to safety and environmental impact is an additional method of 'future proofing' any revised limits.

567 This approach is effectively an 'upgrade' of the current approach and is therefore subject to the same challenge, albeit better catering for uncertainty. The approach could be used to develop revised radionuclide activity levels for D3100, and minimising the number of radionuclides that require limitation in the WAC would provide a better measure of 'future proofing' against the need for future Permit variations than the current approach. However, while it offers some additional flexibility in waste acceptance, it was considered that the upper activity estimates and scenarios that have been identified at this time may still be insufficient to address uncertainty in future waste arisings (see Section 4.3).

8.2.2 Sum of Fractions (SoF) approach

568 The second option considered in the review [335] was a SoF approach where the total activity levels for individual radionuclides are set on the basis of each meeting particular performance measures in isolation. The derived activity levels are thus linked directly to risk, with the calculation relating the performance of the facility, the individual radionuclide properties and the specified performance measure(s).

569 In simple terms, different radionuclides have different properties and give rise to different doses/risks. Determining the amount of each radionuclide that can be safely disposed of requires a radiological assessment – for a single radionuclide, the radiological activity level is calculated from the specific dose/risk determined in the PA from a unit disposal (typically 1 GBq) and the performance measure (i.e. the relevant regulatory criterion to be met). For example, if the calculated specific dose from a radionuclide is 1×10^{-5} μSv/yr per MBq and the regulatory criterion is 20 μSv/yr, then 2 TBq of the radionuclide could be disposed of to meet the criterion if there were no other radionuclides present.

570 A mixture of radionuclides will be present in waste consigned for disposal, and so the approach is to normalise the inventory using the individual radionuclide activity levels during waste acceptance and to sum the normalised values – this is termed the "sum of fractions" [34]. This effectively "weights" the amount of a radionuclide that can be disposed of by its radiological impact, and ensures that the identified performance measure is not exceeded (see Equation (8.1)).

571 The SoF calculation can be expressed in terms of total activity or in terms of a concentration. For example, using the individual radionuclide concentration levels presented in EASR 18 [45, Tab.2], the SoF that determines whether a material is radioactive under EASR 18 is defined using the following equation:

$$\sum_{s=1}^{n} \frac{conc_s}{conc.\,level_s} < 1 \qquad (8.1)$$

where: $conc_s$ = concentration of radionuclide s (Bq g^{-1}).
$conc.\,level_s$ = individual concentration control level specified for radionuclide s (Bq g^{-1}).
n = number of radionuclides (-).

572 It is important to note that there is no single solution to the SoF calculation. More or less of a particular radionuclide can be included with compensatory adjustments in the amount of other radionuclides. Overall, therefore, the approach can be used to assess whether proposals for disposal are viable in terms of how much of a particular waste stream can be accepted and as an overall check that the total activity accepted for disposal meets safety requirements.

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34 The term "sum of fractions" used here is adopted from the international literature. EASR 18 specifies the application of a "sum of quotients" rule for identifying radioactive waste [45, Sch.8, Part 1, ¶4]. The term "sum of quotients" is synonymous with "sum of fractions".

573 A SoF calculation requires that an activity control level or concentration control level is set for each radionuclide that might contribute to the overall impact of any given inventory in terms of the performance measure of concern. This may be:

- set for a specific radionuclide by extrapolation of a PA calculation; or
- set for a group of radionuclides by extrapolation of a PA calculation on the basis that the impact of the group can be covered by a collective level.

574 If a PA calculation is not available, a generic/default control level is used.

575 Radionuclides for which an activity control level or concentration control level is not required in the SoF calculation include any radionuclide that:

- has no impact in terms of the performance measure of concern; or
- is included by virtue of its impact being accounted for within the calculated impact of another radionuclide (its parent); or
- is outside the scope of the performance measure (e.g. naturally-occurring ^{40}K is not included in the calculations for dose compliance with EASR 18).

576 There are several examples of approaches to using PA to calculate activity control levels for SoF calculations. All five LLW and VLLW disposal facilities in England (Calder Landfill, Clifton Marsh Landfill, East Northants Resource Management Facility, Lillyhall Landfill and LLWR) now have permits reflecting radiological limits calculated for a SoF approach [337; 338; 339; 340; 341]. In addition to the international recognition of the approach, as illustrated in [342], SoF is commonly referred to in regulations detailing low-level waste classification for near-surface disposal in the United States (e.g. see [343] for an overview). Yucel *et al.* [344] also discuss a decision-making process involving PA calculations and a SoF approach to manage waste acceptance at a LLW disposal facility in the USA.

577 The main advantage of the SoF approach is the removal of reliance on uncertain estimates of the waste inventory, and the greater flexibility for disposal operations that it brings as a result.

578 The approach is not without its challenges, however. There are over one hundred radionuclides specified in the D3100 inventory, but only a few of these radionuclides contribute significantly to calculations of radiological impact for the different D3100 PA scenarios. It is, therefore, neither beneficial nor cost-effective to track all of the radionuclides individually but, without an accurate prediction of the final inventory, it is not necessarily possible to know whether a radionuclide will be significant. Therefore, it is necessary to track more radionuclides than will likely prove significant in the final PA calculations at closure. It may also be necessary to make assumptions about the final mix of radionuclides when making decisions about managing future disposals. The setting of the control levels using PA results places a reliance on the PA assumptions remaining valid, particularly those to which the PA results are most sensitive. Further, extrapolation of the results to derive a control level from the inventory input to the PA calculation assumes a linear relationship. However, some processes, such as solubility control of concentrations or change in contaminated footprint, can introduce significant non-linearities. Therefore, the validity of the

extrapolation of the results needs to be checked before application of a SoF approach.

579 When using the calculated control levels, the SoF calculation would be used to test compliance during waste acceptance. Separately, the actual disposals of individual radionuclides would be recorded for use in safety case calculations to confirm that the facilities are compliant with the Permit and, therefore, regulatory guidance. As for all options, calculating and tracking the “remaining capacity” will remain necessary for optimising waste stream management.

8.2.3 Selected approach

580 Both of the alternative approaches considered would continue to ensure that waste disposals are adequately controlled such that the assumptions set out in the ESC are met, but they would also enable additional flexibility to account for inventory uncertainty and to optimise disposal of Dounreay LLW. At a high level, the SoF approach appears more logical, as it is based directly on calculations of radionuclide content that D3100 can safely contain rather than on uncertain estimates of predicted waste arisings. It is considered [335] that implementation of the SoF approach would be unlikely to place additional reporting or compliance requirements on the waste consignors, but would be equally unlikely to reduce the requirements, or D3100 compliance verification requirements. Given the inherent challenge associated with defining an accurate inventory for wastes not yet generated and the restrictions that this challenge places on the ability of D3100 to receive certain waste populations, it is proposed to use an optimisation process to control disposals based around a SoF approach. This approach will allow disposals to be balanced with their calculated impact, optimising the balance between disposals and their radionuclide composition by considering a range of possible inventories, wasteforms and designs. This will provide greater operational flexibility for D3100, whilst aligning management practices with those elsewhere in the UK radioactive waste disposal industry.

8.3 D3100 SoF Approach and Proposed Radionuclide Control Levels

581 The SoF approach developed for D3100 is considered in detail in the SoF report [49]. Drawing on that report, this section explains the key assumptions and decisions that underpin the SoF approach applied at D3100, leading to calculation of individual radionuclide activity control levels to be used in SoF calculations for disposals to the vaults. Section 8.4 then discusses how the SoF calculations will be used as part of D3100 waste acceptance.

582 Key to application of the SoF approach is to use the D3100 PA to calculate control levels for individual radionuclides that can then be used in SoF calculations to manage disposals to the vaults. DSRL will use control levels termed Calculated Activity Concentration Levels (CACLs) for individual radionuclides to undertake SoF calculations. The CACLs are set such that each radionuclide, if disposed of separately at that level in all the waste disposed of, would give an impact equivalent to a selected performance measure. The following sub-sections set out the decisions that have been made as a basis for using the PA to calculate activity control levels for each radionuclide in the SoF calculations.

8.3.1 Radionuclide screening

583 The D3100 Run 5 PA calculates the impact of the radioactive wastes in terms of potential exposure of humans to radioactivity after the facilities have been closed. One step in the development of the Run 5 PA to support the D3100 Permit variation has been to review the radionuclide screening performed previously to ensure that all radionuclides are modelled in the PA for which a control level needs to be applied in the SoF calculations. As identified in paragraphs 573-575, a SoF calculation requires that a control level is set for each radionuclide in the inventory that might contribute to the overall impact in terms of the performance measure of concern.

584 Consistent with the screening approach applied in the Run 3 and Run 4 PAs [49; 278; 279], to decide which radionuclides are of potential significance to the calculated performance and which, therefore, should be included in the PA modelling, two screening measures have been applied:

- Contribution of a radionuclide to the estimated D3100 inventory in terms of a percentage of the total alpha and non-alpha (beta/gamma) activities.
- Comparison of the estimated 2020 inventory to the individual radionuclide concentration levels for radioactive material presented in EASR 18 [34, Tab.2], screening in those radionuclides in excess of 1% of the concentration level for defining radioactive material. A value of 1% of the EASR 18 level was applied because there are roughly 100 radionuclides in the inventory and, therefore, should the D3100 waste contain all 100 of these radionuclides at 1% of their respective concentration levels, then the sum of quotients would still only be around 1 (i.e. just in scope of EASR 18). EASR 18 provides radionuclide-specific values for 86 of the 116 radionuclides listed in the 2020 D3100 LLW Inventory (Section 4.3.2), while also providing a default activity concentration level (0.01 Bq g^{-1}) for unlisted radionuclides.

585 However, three screening measures, additional to those in the Run 3 and Run 4 PAs, have also been applied: assumed control period; selection of inventory Case B; and review of radionuclides considered in assessments for other LLW disposal facilities. Each of these is discussed below.

586 The 2020 inventory estimate is based on the data submitted by DSRL to the UKRWI, but this submission does not necessarily account for decay that has occurred since the actual waste generation (or the waste activity that has been generated due to ingrowth). A significant amount of short-lived activity remains in the 2020 inventory for the screening analysis (e.g. ^{147}Pm has a half-life 2.6 years and has not been generated on the site for a number of years, but still has an estimated 2020 inventory of 8 x 10^{10} Bq [47, Case B]). However, although the closure date for D3100 is currently uncertain, should a period of site access control be allowed for, all of the additional radionuclides with a short half-life (e.g. half-lives less than 5 years) will have inventories that will have decayed to below the 1% EASR 18 concentration level and so they can be screened out of the PA calculations. Given the following points, it is reasonable to assume that there will be access controls and containment of the D3100 disposals for at least the next 50 years:

- revocation of the D3100 EASR Permit will likely not occur until after a period of post-closure verification monitoring;
- the low permeability of the D3100 engineering and the packaging will prevent releases to groundwater for at least 100 years [53];
- DSRL currently plans to store higher-activity waste on the Dounreay site until it can be transferred to a suitable disposal facility – such a facility will not be available for a number of decades, thus requiring continued control of the Dounreay site [298]; and
- plans for the Dounreay site end-state foresee a possible period of control of 150 years to allow residual contamination to decay to “no danger” levels [298][35]; these plans are currently being finalised in tandem with discussions on proportionate regulatory control (PRC) of sites and disposals during and after decommissioning.

587 Indeed, it is now considered that there will be a minimum of 50 years of active institutional control over D3100 after closure (see Section 11). Therefore, radionuclides with half-lives of less than 5 years have been screened out of the Run 5 PA calculations unless they might ingrow as part of a decay chain.

588 The Case B upper estimate from the D3100 2020 inventory (Section 4.3.2; LLW inventory including the LLW Pits waste) has been chosen rather than Case C to avoid inclusion in the general analysis of some additional HAW streams in Case C that are unusual in their radionuclide fingerprint and that may or may not be consigned to D3100. Any radionuclides that are found in these waste streams only and that are not, therefore, picked up in the general screening analysis will be captured by the “other” category in the waste acceptance process (see paragraph 590).

589 The above screening measures screen in sufficient radionuclides to account for 99.8% of the D3100 Case B upper estimate activity at 2070 CE. For added assurance against future changes in inventory estimates, the remaining radionuclides in the 2020 inventory were also reviewed against the radionuclides considered in assessments for other LLW disposal facility assessments. The assessments considered were: the 2011 LLWR assessment [299]; the 2014 assessment for the Swedish repository for short-lived intermediate-level waste and LLW (SFR [345]); and the 2012 assessment for the proposed Belgian Category A waste facility [346]. The review focused on long-lived radionuclides, as any short-lived activity will have either decayed before revocation of the D3100 Permit or, should it be ingrowing, will be included in the limit imposed for a parent. Radionuclides generally only associated with HAW were also screened out, but will be considered as part of an “other” group of radionuclides in the SoF calculations (see below).

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[35] The latest NDA Strategy [2, p.141] assumes that control will be maintained over the Dounreay site until 2333, when it is expected that a Scottish waste disposal facility will be available to enable removal of the ILW stored on the site. However, for planning purposes on site, 150 years of control following completion of all decommissioning activities is currently assumed.

590 For radionuclides not screened in to the D3100 PA, it is necessary to either exclude them from the SoF calculations (e.g. they have no impact on the basis of their short half-life) or to apply a generic control. For the longer-lived radionuclides (half-life greater than 5 years) not in the PA, a generic or collective control level is needed to include their inventory in the SoF calculations. The generic control level could be set to the lowest control level calculated for any radionuclide in the PA, or set to a control level for a radionuclide with similar properties (e.g. the same key exposure pathway). It is proposed to use the lowest calculated control levels for any alpha and non-alpha radionuclides in the PA as generic control levels for "other" radionuclides (see paragraph 615). The projected inventory of these "other" radionuclides is such that they take up a very small proportion of the SoF calculation total (< 0.01%). However, this approach creates a project risk that the generic level proves too restrictive in the future (perhaps because of unanticipated inventory arisings) and then the PA might need to be updated to calculate a specific limit for a particular radionuclide. The significance of such an event depends largely on the effort and time then needed to vary the D3100 Permit. This risk has been reduced by developing the D3100 PA to include some long-lived radionuclides for which the inventory projection is currently low, but which have been identified as potentially radiologically significant in PAs for other disposal facilities (see below). Beyond this measure, the risk of other radionuclides being overly restricted by the generic levels is considered to be very small. A cautious trigger will be set to require a review of the "other" radionuclides should their projected inventory at D3100 rise above a small fraction of the SoF total (see paragraph 615).

591 Analysis of the radionuclide screening measures has led to the following decisions, as summarised in Table 8.1:

- The screening analysis for the Run 3 and Run 4 PAs resulted in 38 radionuclides being considered explicitly (highlighted dark green in Table 8.1). Seven additional short-lived radionuclides were included implicitly, by assuming that they were in secular equilibrium with their parents and summing their dose coefficients with those of their parents (highlighted pale green in Table 8.1). Further details are given in the PA reports [278, App.3; 279, App.2]. All of these radionuclides were automatically retained for the Run 5 PA and the SoF calculation.

- Eight additional radionuclides were identified in the updated 2020 inventory Case B estimate that are in excess of 1% of the concentration level for defining radioactive material in EASR 18 and which have a half-life of greater than 5 years (12 radionuclides had half-lives less than 5 years and were screened out). The eight radionuclides are also highlighted dark green in Table 8.1 and have been included in the Run 5 PA.

- Of the other remaining long-lived radionuclides, there were five long-lived radionuclides recorded in the inventory estimate for D3100 in [47] and that have been modelled in two or more other facility assessments – ^{36}Cl, ^{41}Ca, ^{59}Ni, ^{93}Zr and ^{135}Cs. Again, these radionuclides are highlighted dark green in Table 8.1 and have been included in the Run 5 PA.

- Of the remaining 34 long-lived radionuclides reported in the 2020 inventory not included in the PA model, 10 will be included in SoF calculations using a generic alpha-emitter control level and 24 will be included using a generic non-alpha emitter control level (highlighted orange and blue, respectively, in Table 8.1).

592 In conclusion, of the 116 radionuclides reported in the 2020 D3100 inventory and tracked in the DSRL waste management system, the Run 5 PA model has been used to derive explicit control levels for 51 radionuclides for use in SoF calculations, with an additional 34 radionuclides included via generic limits. Seven radionuclides are included implicitly via limits on their parents, and the 24 remaining radionuclides with short half-lives and no production by ingrowth are excluded from the SoF calculations on the basis that a sufficient period of control at D3100 after closure will be provided to allow their decay. Run 5 PA calculation results using the predicted inventory for the 51 radionuclides screened in are reported in Section 7.7.

Table 8.1: Radionuclides modelled in the Run 5 PA and to be included in the SoF calculations. Green highlight indicates a radionuclide modelled explicitly in the PA – pale green shows the 7 radionuclides only modelled implicitly as a short-lived daughter of another modelled radionuclide. Orange and blue highlight shows additional long-lived radionuclides (half-life > 5 years) that are not in the PA but whose inventory will be included in the SoF calculations by using a generic alpha or non-alpha control level, respectively. Radionuclides without highlighting are short-lived and are excluded from the PA and the SoF calculations.

Nuclide	Half-life (y)	Nuclide	Half-life (y)	Nuclide	Half-life (y)	Nuclide	Half-life (y)
H3	1.23E+01	Tc99	2.11E+05	Eu155	4.76E+00	Pa233	7.38E-02
Be10 [1]	1.51E+06	Ru106	1.02E+00	Gd153	6.58E-01	U232	6.89E+01
C14	5.70E+03	Pd107	6.50E+06	Ho163 [1]	4.57E+03	U233	1.59E+05
Na22	2.60E+00	Ag108m	4.18E+02	Ho166m	1.20E+03	U234	2.46E+05
Al26 [1]	7.17E+05	Ag110m	6.84E-01	Tm170	3.52E-01	U235	7.04E+08
Cl36	3.01E+05	Cd109	1.26E+00	Tm171	1.92E+00	U236	2.34E+07
Ar39 [1]	2.69E+02	Cd113m	1.41E+01	Lu174	3.31E+00	U238	4.47E+09
Ar42 [1]	3.29E+01	Sn119m	8.02E-01	Lu176 [1]	3.85E+10	Np237	2.14E+06
K40	1.25E+09	Sn121m	4.39E+01	Hf178n [1]	3.10E+01	Pu236	2.86E+00
Ca41	1.02E+05	Sn123	3.54E-01	Hf182 [1]	9.00E+06	Pu238	8.77E+01
Mn53 [1]	3.70E+06	Sn126	2.30E+05	Pt193 [1]	5.00E+01	Pu239	2.41E+04
Mn54	8.55E-01	Sb125	2.76E+00	Tl204	3.78E+00	Pu240	6.56E+03
Fe55	2.74E+00	Sb126	3.38E-02	Pb205 [1]	1.53E+07	Pu241	1.44E+01
Co60	5.27E+00	Te125m	1.57E-01	Pb210	2.22E+01	Pu242	3.75E+05
Ni59	1.01E+05	Te127m	2.98E-01	Bi208 [1]	3.68E+05	Pu244 [1]	8.00E+07
Ni63	1.00E+02	I129	1.57E+07	Bi210m [1]	3.04E+06	Am241	4.32E+02
Zn65	6.68E-01	Cs134	2.06E+00	Po210	3.79E-01	Am242m	1.41E+02
Se79	2.95E+05	Cs135	2.30E+06	Ra223	3.13E-02	Am243	7.37E+03
Kr81 [1]	2.29E+05	Cs137	3.02E+01	Ra225	4.08E-02	Cm242	4.46E-01
Kr85	1.08E+01	Ba133	1.05E+01	Ra226	1.60E+03	Cm243	2.91E+01
Rb87 [1]	4.92E+10	La137	6.00E+04	Ra228	5.75E+00	Cm244	1.81E+01

Nuclide	Half-life (y)	Nuclide	Half-life (y)	Nuclide	Half-life (y)	Nuclide	Half-life (y)
Sr90	2.88E+01	La138	1.02E+11	Ac227	2.18E+01	Cm245 [1]	8.50E+03
Zr93	1.53E+06	Ce144	7.80E-01	Th227	5.11E-02	Cm246 [1]	4.76E+03
Nb91 [1]	6.80E+02	Pm145 [1]	1.77E+01	Th228	1.91E+00	Cm247 [1]	1.56E+07
Nb92 [1]	3.47E+07	Pm147	2.62E+00	Th229	7.34E+03	Cm248 [1]	3.48E+05
Nb93m	1.61E+01	Sm147	1.06E+11	Th230	7.54E+04	Cf249 [1]	3.51E+02
Nb94	2.03E+04	Sm151	9.00E+01	Th232	1.41E+10	Cf250 [1]	1.31E+01
Mo93	4.00E+03	Eu152	1.35E+01	Th234	6.60E-02	Cf251 [1]	9.00E+02
Tc97 [1]	2.60E+06	Eu154	8.59E+00	Pa231	3.28E+04	Cf252	2.65E+00

[1] Long-lived radionuclide with inventory estimate of 0 Bq in the Case B 2020 upper estimate inventory [47].

8.3.2 Performance measures

593 D3100 must comply with the regulatory standards set out in the GRA [19], compliance with which is demonstrated in this ESC. The SoF approach is intended to help DSRL manage waste disposals such that they are consistent with the assumptions in the ESC. Therefore, the performance measures against which radionuclide impact is assessed in the PA calculations to determine the activity control levels for the SoF calculations are set by the quantitative standards in the GRA, namely Requirements R6 and R7 (see Section 7.2.2).

594 Three assumptions associated with the use of these performance measures have been made:

1. Use of GRA Requirements R6 and R7 means that these performance measures are met irrespective of any period of authorisation (i.e. regulatory control) that occurs.
2. The required performance levels in the GRA against Requirements R6 and R7 are given as guidance levels, not maximum permitted values. However, with the proviso that future optimisation considerations might mean that exceedance of the guidance levels is tolerated, the guidance levels are used here as constraints for the purposes of deriving the SoF control levels. Conversely, no additional contingency has been applied (i.e. using a fraction of the guidance level as the performance measure). It is considered that the optimisation process followed by D3100 ensures that risks are ALARA, rather than the setting of SoF levels, so there is no need to apply a contingency in the SoF levels. Further consideration of uncertainty is given in Section 8.3.5.
3. The lower dose guidance level for prolonged exposures associated with inadvertent human intrusion, rather than the higher dose guidance level for transitory exposures, has been used as the performance level for Requirement R7. Different receptors are subject to different exposure times and a higher regulatory dose guidance level might be more appropriate for those receptors with shorter, more transitory exposure times, such as a borehole driller. However, when considering the impact of individual radionuclides for the SoF calculations, the most exposed

receptor for each radionuclide may be different. Applying different performance levels to different radionuclides according to the most exposed receptor within the same SoF calculation would be both complicated and potentially flawed. Therefore, the lower guidance level for prolonged exposure has been used for each radionuclide as a cautious assumption, irrespective of the actual anticipated exposure time of the receptor.

595 The performance measures based on R6 and R7 concern impacts to humans. An additional performance measure in the GRA is Requirement R9 on environmental radioactivity (see Section 7.9). This measure has been addressed by conducting a check that the resulting activity levels do not have a significant impact on non-human biota.

8.3.3 Assessment scenarios

596 In the UK, two approaches to setting control levels for disposal facilities from a choice of scenarios are reflected in regulatory Permits. The Permit for Lillyhall [347], for example, shows that a single control level is specified for each radionuclide based on the most limiting (highest impact) of all of the scenarios considered for each radionuclide. These control levels are then combined in a single SoF calculation. In contrast, the Permit issued for LLWR [348] specifies separate sets of control levels based on different scenario and exposure pathway combinations. Each set of control levels for LLWR is considered in a separate SoF calculation, with all the SoF calculations required to be less than one.

597 The use of the most limiting scenario in the PA to determine the activity control levels for the SoF calculations is a conservative approach, consistent with the approach taken in an IAEA study to derive activity limits for near-surface waste disposal [342]. However, different scenarios have different probabilities of occurring that are difficult to constrain (particularly if the probability of a scenario-forming event is stochastic or random). If a high-impact scenario has a low, but poorly-constrained, probability, its use in setting control levels for the SoF calculations may lead to unreasonably-biased, more restrictive results. With this in mind, and as discussed in Sections 7.4.2 and 7.4.3, a secondary screening of the scenario-forming events and processes in the Dounreay LLW FEP list was undertaken for Run 5. The scenario-forming disruptive FEPs have been further screened according to their probability or level of speculation. In particular, the scenarios involving ground rupture and the sinking a well or borehole to extract drinking water have been labelled "what-if" analyses on the basis of extremely low likelihood [48, §4.3.1]. This means that they are not used as scenarios to calculate control levels for the SoF calculations.

598 Thus, the SoF control levels have been derived through consideration of the following scenarios (see Sections 7.4 and 7.5 for scenario descriptions):

- the Undisturbed Performance scenario, combining the impacts of the groundwater pathway with the impacts from releases via the gas pathway for radon (via groundwater release of ^{226}Ra) and ^{14}C (if it is considered that the receptor for each pathway could be the same and could be exposed to releases via each pathway at the same time, otherwise the most limiting of either pathway is used); and

- the Disturbed Performance inadvertent human intrusion scenario, as, excluding the "what-if" analyses, only the human intrusion scenarios give calculated impacts potentially in excess of those determined for the groundwater and gas exposure pathways (see Section 7). The most limiting of the intrusion scenarios and receptors for each radionuclide is used, with the scenarios considered to be mutually exclusive.

599 The inadvertent human intrusion scenarios generally consider exposures to small volumes of waste compared to the total volume of waste in a vault, and the control level is most readily specified in terms of a concentration, thus resulting in calculated activity concentration levels (CACLs). Conversely, the groundwater and gas pathways mix the releases from all of the wastes in the facilities or in a vault into a single volume and the control level is, therefore, most readily specified for these pathways in terms of a total activity, thus resulting in calculated total activity levels (CTALs). However, a CACL can be used to calculate an equivalent CTAL by assuming a total mass of material that will be consigned to D3100 (or conversely a CACL can be calculated from a CTAL).

8.3.4 Assessment timescales

600 For both the groundwater and gas pathways, different radionuclides give peak impacts at different times after closure. For the inadvertent human intrusion calculation, the impact is determined at the time of the intrusion and the calculation is undertaken for intrusion potentially occurring each year after the period of control ceases. As a result of these considerations, it is apparent that using selected time intervals would yield different results that would mean different activity control levels being calculated. Alternatively, different SoF calculations can be specified for groups of radionuclides on the basis of the timing of their peak impacts. One example of grouping of radionuclides in an Environmental Permit is for Clifton Marsh [340; 349]. Here, the grouping is mainly on the basis of similar half-lives, types of radioactive decay, and similar release and migration behaviour.

601 For simplicity, no split of the SoF calculations on the basis of timescales is proposed for D3100. The potential significance of this assumption was tested separately for control levels calculated using the groundwater pathway and for control levels calculated using the human intrusion scenarios (see [49, §4.1]). The results showed that some additional "capacity" could be gained for radionuclides with peak impacts at earlier times, but the calculated control levels for these radionuclides are anyway generally large and disposals of these radionuclides are therefore not restricted. However, the benefit of splitting the SoF calculations for radionuclides with peak impacts at longer timescales was found to be small, such that using a single grouping in the SoF calculation is not unduly restrictive for the radionuclides with a long-term peak impact in comparison to two SoF calculations considering groups based on longer-term and shorter-term impacts separately. Therefore, it was determined that it would be better to focus on further constraining the inventory rather than making the SoF calculations more complex by splitting radionuclides into groups based on timing of peak impacts. Thus, the control level for each radionuclide in the SoF calculation has been determined from its peak impact, irrespective of when that peak occurs.

8.3.5 Uncertainty treatment

602 The D3100 PA addresses the treatment of uncertainty; in addition to scenario uncertainty, there is both uncertainty and variability in the modelling and parameterisation of the system. In some cases, the development of the PA makes cautious assumptions regarding choice of models and parameter values to capture or bound uncertainty. In other cases, a range of possible choices is set out and a series of PA calculations is undertaken to examine the sensitivity of the calculated impacts. The SoF control levels discussed here have been derived using best estimates for the modelling assumptions and parameter values in all of the PA calculations. It is considered inappropriate to use extreme values as this might unreasonably constrain disposals. The SoF approach is a tool to manage the disposal inventory so that it is acceptable within the assumptions set out in the ESC. Using extreme parameter values as an input would bias the use of the SoF approach towards a pessimistic and sub-optimal solution. The best estimate PA calculations are anyway generally cautious when addressing uncertainties. Further, the decisions made regarding the approach to the SoF calculations are also cautious and have chosen to use the most limiting scenarios and the most exposed receptors, while not pursuing some options, such as grouping of radionuclides, to improve transparency. The same considerations apply to the use of the GRA guidance levels as performance measures, rather than a fraction of the guidance levels. Use of best estimate parameter values and GRA guidance levels is consistent with the calculation of activity control levels for other UK facilities (e.g. LLWR 2011 [337]; Clifton Marsh 2010 [340]; Lillyhall 2009 [339] and 2018 [350]; Augean (East Northants) 2015 [351]).

8.3.6 Derivation of control levels

Groundwater pathway

603 CTALs are calculated for the groundwater pathway using the following equation:

$$CTAL_{Rn} = \left(\frac{R_{GRA}}{Peak\ R_{Rn}}\right) I_{model} \tag{8.2}$$

where: $CTAL_{Rn}$ = calculated total activity control level of radionuclide *Rn* in either the LLW vaults or Demolition LLW vaults (Bq).

R_{GRA} = risk guidance level from the GRA (per year).

$Peak\ R_{Rn}$ = peak risk calculated from radionuclide *Rn* within a specified timeframe of interest to the most limiting receptor via the groundwater pathway (per year).

I_{model} = initial inventory of radionuclide *Rn* assumed in the Run 5 PA run used to calculate the peak risk (Bq).

604 For the Run 5 PA calculations used to derive CTALs, a unit inventory was assigned to each group of vaults in the PA calculation: LLW1 and LLW2; LLW3; and Demolition LLW1 and Demolition LLW2. The extrapolation of the PA results to determine the CTAL assumed a linear relationship between the inventory and the dose. The validity of this assumption was checked [49]. Solubility control is not a significant issue for D3100 and, anyway, would reduce releases and increase CTALs compared to those

calculated. The PA results are not necessarily linear with assumptions about the dimensions of the disposal system and so a bounding case of maximum dimensions based on the D3100 planning permission has been used. Separate CTALs were derived for the LLW vaults and the Demolition LLW vaults because the conceptual models and calculated release rates of radioactivity from the two types of vault differ. The SoF report [49, §4.2] showed that it is not possible to take the simplifying position that the CTAL for the LLW vaults is always the most constraining of the two, as the calculated LLW CTAL does not consistently exceed the Demolition LLW CTAL for all radionuclides. This result reflects different retention behaviours in the two waste types and their respective vault engineering. For example, the conceptual model used in the D3100 PA applies degraded cement properties to the Demolition LLW, while intact cement properties are applied initially to the grouted LLW. There is also an earlier assumed transition to more oxidising conditions in the Demolition LLW vaults compared to the LLW vaults as iron materials are depleted more slowly in the latter. This results in radionuclides such as ^{90}Sr and ^{137}Cs being released more slowly from the Demolition LLW vaults compared to the LLW vaults, leading to a higher CTAL for these radionuclides in the Demolition LLW, but the opposite is the case for radionuclides such as ^{94}Nb and ^{79}Se.

Gas pathway

605 The Run 5 PA gas pathway model calculates a ^{14}C risk assuming that the inventory is evenly spread across a defined surface area of one or more LLW vaults[36] (Section 7.5.3). The risk calculated for ^{14}C for the groundwater pathway and the risk calculated for the gas pathway are summed since they overlap and could be received by the same receptor. However, the disposed of ^{14}C inventory can give an impact only by one or the other pathway (although the groundwater pathway calculation does not actually account for the loss of any ^{14}C in gas). Therefore, a CTAL for ^{14}C is calculated using the following equation:

$$CTAL_{C-14} = \left(\frac{A_{CTAL}}{A_I}\right)\left(\frac{R_{GRA}}{[0.06 Flux_{C-14,gas}\ Dose_{Flux}\ \ Risk_A]}\right) I_{C-14} + \left(\frac{R_{GRA}}{R_{C-14,GW}}\right) I_{C-14} \tag{8.3}$$

where: $CTAL_{C\text{-}14,gas}$ = calculated total activity control level for ^{14}C (Bq).

A_{CTAL} = area of vaults for which the CTAL is being calculated (i.e. that will contain the ^{14}C) (m^2).

A_I = area of vaults containing the inventory I in the PA calculation (m^2).

R_{GRA} = risk guidance level from the GRA (per year).

$Flux_{C\text{-}14,gas}$ = peak ^{14}C-containing gas flux released from the LLW vaults (Bq per m^2 per year).

$Dose_{Flux}$ = dose received from the ^{14}C-containing gas flux released from the LLW vaults (Sv per year per Bq per m^2 per year).

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36 No ^{14}C-bearing gas is assumed to be generated in the Demolition LLW vaults owing to the lack of organic material to degrade in the waste.

$Risk_A$ = risk or expectation value that the LLW vault cap area might be used for growing food (-).
0.06 = GRA conversion for dose to risk (per Sv).
$R_{C\text{-}14,GW}$ = peak risk from ^{14}C via the groundwater pathway (per year).
$I_{C\text{-}14}$ = inventory of ^{14}C assumed in the PA run used to calculate the flux and groundwater risks (Bq).

606 For ^{226}Ra, the Run 5 PA gas pathway model calculates a risk from radon released by the decay of ^{226}Ra transported to the soil by releases of ^{234}U and daughters to groundwater (Section 7.5.3). Therefore, the risk calculated for the groundwater pathway and the risk calculated for the gas pathway for ^{226}Ra and parents are again additive as the same receptor might be exposed to both pathways. In this case however, unlike for ^{14}C, the same ^{226}Ra concentration in the soil gives the calculated impacts from both pathways. Therefore, a CTAL for ^{226}Ra is calculated as follows, repeating the calculation for each ^{226}Ra parent (^{230Th}, ^{234}U, ^{238}Pu, ^{238}U, ^{242}Pu and ^{242m}Am) to determine the contribution of ingrowing ^{226}Ra to the CTAL of the parent:

$$CTAL_{Ra-226} = \left(\frac{R_{GRA}}{[R_{Ra-226,soil} + R_{radon}]}\right) I_{Ra-226} \tag{8.4}$$

where: $CTAL_{Ra\text{-}226}$ = calculated total activity control level of ^{226}Ra in either the LLW vaults or Demolition LLW vaults (Bq).
R_{GRA} = risk guidance level from the GRA (per year).
$R_{Ra\text{-}226,soil}$ = peak risk calculated from ^{226}Ra in soil via the groundwater pathway (per year).
R_{radon} = peak risk from radon gas in a dwelling built on soil contaminated by ^{226}Ra via the groundwater pathway (per year).
$I_{Ra\text{-}226}$ = initial inventory of ^{226}Ra (or parent) assumed in the PA groundwater pathway model used to calculate the risks (Bq).

Inadvertent human intrusion

607 For the PA human intrusion model, the dose calculation is based on an activity concentration in the waste and so CACLs have been calculated using:

$$CACL_{Rn} = \left(\frac{D_{GRA}}{Peak\ D_{Rn}}\right) \frac{I_{model}}{M_{vault}} \tag{8.5}$$

where: $CACL_{Rn}$ = calculated activity concentration control level of radionuclide *Rn* in either the LLW vaults or Demolition LLW vaults (GBq per tonne).
D_{GRA} = dose guidance level from the GRA (mSv per year).
$Peak\ D_{Rn}$ = peak dose calculated from radionuclide *Rn* to the most limiting receptor within a specified timeframe of interest via the human intrusion pathway (mSv per year).
I_{model} = initial inventory of radionuclide *Rn* assumed in the PA run used to calculate the dose (Bq).
M_{vault} = total mass of material in the vault into which the intrusion occurs (tonnes).

608 A separate calculation for each waste-type (LLW and Demolition LLW) is needed on account of different waste properties (e.g. densities, porosities, retardation coefficients) potentially leading to different limiting exposure scenarios.

609 The CACLs are based on the peak calculated impact between the end of the period of institutional control from 2020 CE and 50,000 years, after which the assumption of no leaching in the human intrusion pathway model can no longer be considered to be valid [48, §8.6].

610 The most exposed receptor from the Run 5 inadvertent human intrusion scenarios has been used to calculate the CACL for each radionuclide. For the majority of radionuclides, this is either the Borehole Resident (most non-alpha emitters) or the Borehole Worker (most alpha emitters). The same receptor is generally the most exposed for inadvertent intrusion into either the LLW vaults or the Demolition LLW vaults. However, the CACLs for the Demolition LLW vaults are slightly higher as the assumed waste density is slightly lower and the borehole scenario considers a waste/vault height of 9.1 m versus 11.1 m for the LLW vaults. For ^{60}Co and ^{137}Cs, there is also a difference between the CACLs for LLW and Demolition LLW because the Uncontrolled Intruder is the most exposed receptor for these radionuclides for intrusion into the LLW vaults, but the Borehole Resident is the most exposed receptor for these radionuclides for intrusion into the Demolition LLW vaults.

Results

611 The equations above show that the activity control levels are calculated by linearly extrapolating the inventory used in the PA calculations such that the corresponding risk from the groundwater pathway (and the gas pathway for ^{14}C and ^{226}Ra) or dose from the human intrusion scenarios would equal the regulatory risk (10^{-6} y^{-1}) or dose (3 mSv y^{-1}) guidance level, respectively.

612 The most exposed receptor is used for the calculation of the CTAL or CACL for each radionuclide in each calculation. For the majority of radionuclides in the groundwater pathway, the most exposed receptor is the Crofting Community RP (which accounts for the probability of exposure). However, in some cases, the impact of a radionuclide is particularly dominated by the foreshore/marine exposures and the Winkler RP is the most exposed receptor owing to consumption of seafood at a high rate. For the human intrusion scenarios, the maximum dose from a single radionuclide is generally calculated either for the resident of a house with a garden containing spoil from a borehole drilling investigation (mostly non-alpha emitting radionuclides) or for the worker drilling the boreholes during the investigation (mostly alpha emitting radionuclides). However, there can be some variability in the key receptor for certain radionuclides – in particular, the Uncontrolled Intruder can be dominant in some cases. Taking the most exposed or constraining receptor for each radionuclide is cautious, but avoids complexity in deriving separate SoF calculations and associated control levels for several receptors.

613 The CTALs derived for each radionuclide using the Run 5 PA groundwater and gas pathway models were compared with the corresponding CACLs derived using the human intrusion model for 50 years control [49, §5.1.3]. The CTALs were re-scaled to GBq te^{-1} using the packaged waste volumes in the D3100 planning permission multiplied by the waste densities used in the human intrusion PA calculations. The densities used in the PA calculations are generally higher than the densities of the

packaged wastes derived from the UKRWI submission data in [47]. Therefore, the re-scaling of the CTALs with the higher densities is cautious in that it produces lower CACLs.

614 For most of the radionuclides, the lowest CACL derives from the human intrusion results. Therefore, the proposed control levels for use in SoF calculations for D3100 are presented in Table 8.2 as CACLs, with the control levels deriving from the groundwater and gas pathway recalculated as CACLs. Thus, the proposed CACLs always reflect the most limiting scenario. This will remain the case provided that the total volumes of waste do not go above the estimates for the full D3100 footprint used in the comparison of the groundwater and human intrusion results.

615 The control levels set for the “other” radionuclides in LLW are the lowest CACL for a non-alpha emitter (^{108m}Ag) and the lowest CACL for an alpha emitter (^{226}Ra). The lowest alpha emitter in Demolition LLW is also ^{226}Ra, but the lowest non-alpha emitter changes to ^{79}Se. The 34 “other” radionuclides are long-lived (greater than 5 years) and are recorded with an insignificant activity in the 2020 D3100 inventory estimate (Section 4.3.2). Should an unexpected quantity of an “other” radionuclide occur in the future, it could start to take up a noticeable proportion of the SoF total using the conservative “other” limits. At this point, an evaluation of a need for further action, such as running the PA for the radionuclide of interest, can be made. It is proposed that the quantity triggering such an evaluation is set at conservative 1% of the calculated SoF total for D3100.

616 Comparing the CACLs for the LLW and Demolition LLW vaults, the human intrusion calculations generally give lower impacts and higher CACLs for the Demolition LLW vaults. This is mainly because the lower vault height for the Demolition LLW vaults (9.1 m compared to 11.1 m) means that less waste is involved in vertical intrusions in the PA model. The groundwater and gas pathway calculations give different impacts for disposals to the LLW and Demolition LLW vaults because of different engineering, different waste properties, and different activity release rates. Compared across the individual radionuclides, there is no consistent difference between the CACLs for the Demolition LLW vaults and the LLW vaults. For this reason, it is proposed to apply different control values in separate SoF calculations for each waste type.

Table 8.2: Proposed Calculated Activity Concentration Levels (CACLs) in GBq/te for application to the D3100 LLW and Demolition LLW vaults. Blue and green highlight show the lowest limits calculated for an alpha and a non-alpha-emitting radionuclide – these are used as the CACLs for “Others” at the foot of the table.

LLW		Demolition LLW	
Radionuclide	Proposed CACL (GBq/te)	Radionuclide	Proposed CACL (GBq/te)
^{3}H	3.1E+03	^{3}H	3.8E+03
^{14}C	1.8E+01	^{14}C	9.1E-02
^{36}Cl	8.6E-01	^{36}Cl	1.1E+00
^{41}Ca	1.7E+02	^{41}Ca	7.1E+01

LLW		Demolition LLW	
Radionuclide	Proposed CACL (GBq/te)	Radionuclide	Proposed CACL (GBq/te)
^{59}Ni	6.1E+03	^{59}Ni	4.6E+03
^{60}Co	4.7E+02	^{60}Co	7.3E+02
^{63}Ni	3.6E+03	^{63}Ni	4.4E+03
^{79}Se	2.4E-01	^{79}Se	1.7E-02
^{90}Sr	3.0E+01	^{90}Sr	3.7E+01
^{93m}Nb	1.0E+05	^{93m}Nb	1.2E+05
^{93}Zr	1.7E+03	^{93}Zr	2.1E+03
^{93}Mo	2.4E+01	^{93}Mo	8.0E+00
^{94}Nb	1.6E+00	^{94}Nb	1.9E+00
^{99}Tc	2.9E+00	^{99}Tc	3.5E+00
^{107}Pd	4.3E+03	^{107}Pd	5.3E+03
^{108m}Ag	1.0E-01	^{108m}Ag	1.8E-01
^{121m}Sn	1.4E+02	^{121m}Sn	1.7E+02
^{126}Sn	1.1E+00	^{126}Sn	8.4E-01
^{129}I	1.2E-01	^{129}I	5.5E-02
^{133}Ba	2.1E+02	^{133}Ba	1.4E+02
^{135}Cs	3.6E+01	^{135}Cs	1.7E+01
^{137}Cs	4.7E+00	^{137}Cs	1.6E+01
^{151}Sm	9.2E+03	^{151}Sm	1.1E+04
^{152}Eu	2.8E+01	^{152}Eu	3.4E+01
^{154}Eu	1.1E+02	^{154}Eu	1.3E+02
^{210}Pb	1.0E+01	^{210}Pb	1.3E+01
^{226}Ra	2.2E-02	^{226}Ra	2.6E-02
^{227}Ac	2.4E-01	^{227}Ac	2.9E-01
228Th	1.9E+07	228Th	2.4E+07
^{228}Ra	1.3E+02	^{228}Ra	1.6E+02
229Th	2.2E-01	229Th	2.7E-01
230Th	2.3E-02	230Th	2.8E-02
^{231}Pa	3.9E-02	^{231}Pa	4.8E-02
^{232}U	7.7E-01	^{232}U	9.3E-01
^{232}Th	2.7E-01	^{232}Th	3.3E-01
^{233}U	2.5E-01	^{233}U	3.0E-01
^{234}U	6.4E-02	^{234}U	7.8E-02
^{235}U	6.0E-02	^{235}U	7.3E-02
^{236}U	8.3E+00	^{236}U	7.5E+00
^{237}Np	6.4E-01	^{237}Np	7.8E-01
^{238}Pu	8.9E-01	^{238}Pu	1.1E+00
^{238}U	8.5E-01	^{238}U	1.0E+00

LLW		Demolition LLW	
Radionuclide	**Proposed CACL (GBq/te)**	**Radionuclide**	**Proposed CACL (GBq/te)**
^{239}Pu	5.5E-01	^{239}Pu	6.7E-01
^{240}Pu	5.5E-01	^{240}Pu	6.8E-01
^{241}Am	7.1E-01	^{241}Am	8.7E-01
^{241}Pu	2.2E+01	^{241}Pu	2.6E+01
^{242}Pu	5.7E-01	^{242}Pu	7.0E-01
^{242m}Am	6.3E-01	^{242m}Am	7.7E-01
^{243}Cm	2.9E+00	^{243}Cm	3.5E+00
^{243}Am	6.7E-01	^{243}Am	8.1E-01
^{244}Cm	6.7E+00	^{244}Cm	8.1E+00
Other Alpha‡	2.2E-02	Other Alpha	2.6E-02
Other Non-Alpha*	1.0E-01	Other Non-Alpha	1.7E-02

‡ Other Alpha limit applies to the sum of the following 10 radionuclides: ^{147}Sm, ^{210m}Bi, ^{244}Pu, ^{245}Cm, ^{246}Cm, ^{247}Cm, ^{248}Cm, ^{249}Cf, ^{250}Cf, and ^{251}Cf.

* Other Non-Alpha limit applies to the sum of the following 24 radionuclides: ^{10}Be, ^{26}Al, ^{39}Ar, ^{42}Ar, ^{40}K, ^{53}Mn, ^{81}Kr, ^{85}Kr, ^{87}Rb, ^{91}Nb, ^{92}Nb, ^{97}Tc, ^{113m}Cd, ^{137}La, ^{138}La, ^{145}Pm, ^{163}Ho, ^{166m}Ho, ^{176}Lu, ^{178n}Hf, ^{182}Hf, ^{193}Pt, ^{205}Pb, and ^{208}Bi.

8.4 Application during Waste Acceptance and Compliance Requirements

8.4.1 Assurance of compliance using the proposed approach

617 It is proposed that the generic LLW and Demolition LLW activity definitions are used in conjunction with the SoF calculated activity concentration control levels (CACLs) presented in Table 8.2 to help manage waste acceptance at D3100. The SoF totals for LLW and Demolition LLW vault disposals will be calculated as follows:

$$\sum_{Rn=1}^{n} \frac{A_{LLW,Rn}}{CACL_{LLW,Rn}} < 1$$
$$\sum_{Rn=1}^{n} \frac{A_{Demo\ LLW,Rn}}{CACL_{Demo\ LLW,Rn}} < 1 \qquad (8.6)$$

where: $A_{LLW,Rn}$ = activity concentration of radionuclide *Rn* in disposals to the LLW vaults (GBq/te).

$CACL_{LLW,Rn}$ = calculated activity concentration level for radionuclide *Rn* in the LLW vaults – see Table 8.2 (GBq/te).

$A_{Demo\ LLW,Rn}$ = activity concentration of radionuclide *Rn* in disposals to the Demolition LLW vaults (GBq/te).

$CACL_{Demo\ LLW,Rn}$ = calculated activity concentration level for radionuclide *Rn* in the Demolition LLW vaults – see Table 8.2 (GBq/te).

n = number of radionuclides in the calculations (-).

618 For most radionuclides, the CACLs are based on the inadvertent human intrusion scenario and so the LLW and Demolition LLW vaults are anyway independent. For the few radionuclides where the CACLs are based on the groundwater and gas pathway (^{14}C, ^{41}Ca, ^{79}Se, ^{93}Mo, ^{129}I and ^{135}Cs), the rescaling of the CTAL to give a CACL uses bounding assumptions about the waste volumes. Therefore, treating the two vault systems as separate (i.e. not combining LLW and Demolition LLW in a single SoF calculation) will not cause the cumulative risks to exceed the regulatory risk guidance level. Ensuring that Equation (8.6) is satisfied for each vault in the D3100 disposal facilities will, along with disposal records, ensure compliance with the varied Permit and consistency with the ESC.

619 Comparison of the control levels with the latest inventory estimates provides assurance in the SoF proposal. The SoF report [49, §5.2.3] presents an example SoF calculation using the best and upper estimates for the Case B LLW inventory [47]. For this inventory projection, the radionuclides of most significance (i.e. those contributing most to the SoF total) in the LLW vaults are ^{226}Ra and ^{234}U, with a lesser contribution from ^{137}Cs, the Pu-isotopes and ^{241}Am. Together, these isotopes contribute some 90% or more of the SoF total for the waste. The calculated SoF total for the Case B best estimate inventory is 0.11, rising to 0.36 for the upper estimate. These example calculations show that, on the basis of the control levels determined using the D3100 PA, the best and upper estimates of the Case B LLW inventory would be safe in terms of post-closure impacts. Even when considering Case C, which includes three ILW/LLW boundary streams that are being assessed for their suitability for disposal in D3100, the SoF total for the upper estimate Case C inventory is only 0.51. The SoF total for the average activity concentration in the HHISOs disposed of to-date is 0.06 [49, §5.3.3].

620 An equivalent calculation for the best and upper estimate Demolition LLW inventories [49, §5.2.4] results in SoF totals at least an order of magnitude lower than those for LLW (0.002 and 0.02, respectively). Again, therefore, the results indicate that, on the basis of the control levels determined using the D3100 PA, the estimated Demolition LLW inventory would be safe post-closure. The inventory estimate for Demolition LLW [47] does not have much ^{226}Ra, but otherwise it is the same radionuclides as for LLW that make up most of the SoF total – namely ^{234}U together with ^{137}Cs, ^{90}Sr, Pu-isotopes and ^{241}Am.

621 The SoF report [49, §5.5] presents a scoping assessment of the impact of key radionuclide concentrations in the environment that correspond to the proposed LLW CACLs using the ERICA Tool [323] (see Section 7.9 for an ERICA assessment considering the Case B inventory). The calculations have been undertaken for peak concentrations of ^{79}Se and ^{90}Sr for beta/gamma emitters and ^{234}U and ingrowing daughters for alpha emitters – these were the most significant contributors to calculated impacts in the previous D3100 assessment [324]. The results of the scoping calculation presented here are consistent with those of the previous assessment [324], and those presented in Section 7.9, in that the individual risk quotients associated with radionuclides disposed of at their CACLs are low for the terrestrial environment and the individual risk quotients for the marine environment are even lower. However, the risk quotients for the freshwater environment are

generally above one. As discussed in paragraph 539, this finding needs to be considered in the context of the conservative approach applied for the freshwater ecosystem, where it is highly cautious to assume that the surface water environment around D3100 could support the types of freshwater reference organisms considered in the ERICA database. Further, the concentration limits suggested for radionuclides such as ^{226}Ra and ^{234}U using the ERICA Tool are lower than naturally-occurring background concentrations – indicating that the screening criterion for the impact from D3100 is actually set well below the dose levels that organisms will receive naturally (see paragraph 539). Finally, the calculated concentrations are similar to current day levels (see Table 7.13). Therefore, the proposed CACLs are not considered to present an undue risk to the protection of non-human biota.

622 For additional assurance regarding the reasonableness of the proposed control levels, the SoF report [49, §5.4] presents comparisons with calculations from other studies. Whilst needing to account for the different assumptions between the studies, the results were found to be comparable, and the differences understandable, when considering IAEA guidance [58], the 2011 LLWR PA [337], and the DSRL Derived Concentration Guideline Levels (DCGLs) [352].

8.4.2 Flexibility and ongoing optimisation

623 For both vault types, the proposed waste management means that the SoF total should be less than one at closure. SoF calculations can be undertaken and reported periodically using a running average of activity concentration in consignments before a vault is filled. However, it is only when all of the disposals to a vault are complete that the SoF total across the vaults should be less than one for each waste type. Before this point, the SoF calculations can be used as needed for dialogue with SEPA to discuss any issues with ongoing operations. Until all of the vault space has been filled, however, the final SoF total will not be known with certainty. In order to estimate the eventual SoF total, an estimate of the remaining disposals will be needed. Periodically updating the estimated activity of future D3100 disposals, using the DSRL PWI database, to consider the associated SoF total will support planning for future phases of construction at D3100 and feed back to the Dounreay site for the planning of decommissioning and waste consignment.

624 D3100 can also undertake SoF calculations at a range of scales during waste acceptance and disposal operations, partly to provide flexibility during waste and load management and partly to guide consignment and optimal management of problematic wastes. These *ad hoc* SoF calculations will inform waste management decisions, but will not be used as formal acceptance criteria and will not necessarily be applied to every waste consignment. A SoF calculation can be conducted at any time prior to completion of waste emplacement in a vault to identify if a phase of consignment of higher-than-average activity packages, such as might happen during the decommissioning of a particular structure, might be an issue needing attention during load management. The calculation can be undertaken before the vaults are filled by assuming that the remainder of the vault is occupied by waste at the average activity concentration of disposals to-date, or by making bounding assumptions about completion of disposals using waste with higher activity concentrations.

625 Analysing the impact of future waste streams at the point when a Project Specific Waste Plan (PSWP) is developed or updated for a decommissioning project will enable advice on the management of individual waste streams for disposal to be given to the consignors at an early stage, such as which radionuclides are important for the developing characterisation plans. This will be particularly important if the waste stream contains significant activity due to key radionuclides and/or the characterisation uncertainty associated with those radionuclides is high. It may be possible to advise on mixing of waste streams in consignments to ensure that the SoF total for a consignment is less than one. Analysing such information at an early stage will also help D3100 to determine if a particular waste stream may disproportionately consume the available “capacity” for certain radionuclides.

626 On scales smaller than that of a vault, the SoF approach enables DSRL to apply flexibility in the management of individual packages within the context of ultimately meeting compliance with the Permit when the vaults are filled. During acceptance of individual consignments, D3100 applies an acceptance criterion that the packages meet the appropriate waste definition, LLW or Demolition LLW. The waste definitions are in terms of GBq/tonne, but the test is applied at the scale of a package (e.g. HHISO, Demolition LLW bag, non-containerised item). The significance of heterogeneity at a smaller scale is considered in the SoF report [49, §6.3.3], where it is concluded that the waste definition test at the package level is consistent with the stylised scenarios used to assess performance of D3100.

627 It may be that a few packages satisfy the LLW definition but exhibit, on the package-scale, a SoF total greater than one. However, good load management practice [127] will mean that, as far as reasonably practicable, any such packages are evenly distributed in D3100. Therefore, the average waste concentration in the vault at the scale of relevance for the limiting scenario will remain consistent with an overall SoF total of one. For example, if the limiting scenario is intrusion by a drilling investigation involving two boreholes, then the scale of relevance to the PA calculation will be the average activity concentration across any two stacks of packages. Even if a single package or packages have activity concentrations above the CACLs, the SoF total for the two stacks as a whole will be less than one and the PA calculation will be consistent with the GRA performance measure.

628 Most radionuclides are limited by the borehole intrusion (driller or subsequent resident) scenario [49, §6.3.3]. However, for some radionuclides limited by the human intrusion results (^{60}Co, ^{137}Cs and ^{108m}Ag for LLW), the uncontrolled intruder is the limiting scenario. Although the volume of material in the scenario is not defined – the intruder is simply assumed to be exposed to undiluted waste [48, Tab.5.14] – the nature of the scenario involving direct excavation is such that the waste could come from a single HHISO. Waste records will allow any packages with high concentrations of these radionuclides to be identified during waste acceptance evaluations. Optimisation of their disposal will be considered against the nature of the limiting scenario and the options offered by load management (e.g. placing the containers towards the base of the vaults to further reduce the likelihood of an intruder digging down to such wastes).

8.4.3 Assumptions and ESC management

629 The activity control levels calculated using the PA and used in the SoF calculations reflect the design of D3100 and the assumptions made. Should fundamental changes be made in the design and layout of the facilities, then new PA calculations and revised CACLs might be needed. However, the proposed CACLs are based mostly on the human intrusion pathway and, in general, these calculations are not sensitive to changes in layout of the vaults or understanding of the geosphere. The PA also makes use of stylised scenario assumptions to manage uncertainties, and so the PA results are robust to future developments. Given the amount of work on optimisation and PA development that has already been undertaken on D3100, it is unlikely that any changes in the future will lead to large decreases in calculated risks. Therefore, the only foreseeable reasons for requiring revision of the SoF calculations in the future would be a change in regulatory guidance levels, a change in the tolerance of uncertainty (e.g. applying a different interpretation of the guidance levels as performance measures), or the addition of a new specific radionuclide CACL as described in paragraph 615 (which is not considered likely).

630 As part of managing any future changes, the SoF report identifies the key assumptions made in development of the SoF approach that need to be considered during future ESC management [49, §6.5]. The assumptions concern either the proposed CACLs themselves or their overall and collective validity with regard to the ESC, and include aspects such as the assumed thickness and density of waste in the vaults, the contaminated footprint of the D3100 vaults and total waste volume, PA parameter value assumptions, changes in the inventory of “other” radionuclides and material breakdown, and the 50 year control period assumed in screening the radionuclides.

FP.9	Maintain, review and further develop as necessary the SoF approach for waste acceptance and management.

9 ADDITIONAL SAFETY CONSIDERATIONS

631 In addition to the quantitative evaluation of safety presented in Section 7, this section presents further evidence and arguments for the safety of D3100 by addressing the detailed requirements in the GRA related to qualitative safety considerations. The first section of this section therefore considers the assurance provided by the design for strength in depth (i.e. safety is not reliant on any one single component of the disposal system), and the second section considers the significance of the results from the safety assessments. The last section considers why there is confidence in the quantitative safety assessments.

632 Safety features that provide confidence in the environmental safety of D3100 include:

- Good design, for example
  - using an isolate-and-contain strategy;
  - multiple engineered barriers;
  - reliance on passive long-term safety; and
  - choosing a suitable stable site and adapting to the site characteristics, as required.
- Low hazardous nature of the LLW, for example
  - limiting the near-field source term through waste acceptance requirements.
- Quality of implementation, for example
  - working within a well-defined legal and regulatory framework;
  - using the well-established DSRL management system, further developed to provide an appropriate degree of separation between the waste consignor and waste acceptance functions;
  - demonstrating optimisation;
  - applying waste acceptance requirements and an emplacement strategy via an optimised load management plan;
  - adequate resourcing; and
  - using commissioning tests, where practicable.
- Safety assurance, for example
  - demonstrating operational and post-closure environmental safety;
  - monitoring performance, as necessary;
  - optimising closure;
  - using independent scrutiny and peer review of key project documentation and construction quality; and
  - protecting the site using both active controls (e.g. site monitoring) and passive controls (e.g. anti-intrusion layer in the cap).

9.1 Good Design and Strength in Depth

GRA 7.2.1(b)	The environmental safety case needs to show how the various components of the disposal system contribute to meeting the requirements.
GRA 7.3.2	The disposal system will consist of multiple components or barriers. There is a distinction between these components and the environmental safety functions they provide.
GRA 7.3.3(a)	The environmental safety case should include an explanation of, and substantiation for, the environmental safety functions provided by each part of the system. It should also identify which radionuclides each function is relevant to and the expected time period over which the function is effective.
GRA 7.3.3(b)	The environmental safety case for the period after closure of a disposal facility should not depend unduly on any single function.
GRA 7.3.4	Explore the contribution that each environmental safety function makes to the environmental safety case (for example, by sensitivity analyses). Explore the circumstances where more than one function is impaired.
GRA 6.2.29	After the end of the period of authorisation, rely entirely on a combination of engineered measures that can contribute to passive safety (recognising the lifetime for which such features can be expected to remain effective) and natural features and processes.
GRA 6.4.10(a)	Show that the geological, hydrogeological and other characteristics of the region and the site under present and reasonably foreseeable future conditions will allow the environmental safety case for the facility to be made.

633 Stage 2 design studies [139; 144; 145; 146; 147] addressed optimisation of the location and manner of waste disposals at Dounreay. Stage 3 design studies have continued the process of optimisation through detailed design [148; 149]. Studies have developed, and will continue to develop, based on understanding of the site and performance of the facilities gained through site characterisation and PA calculations, and through experience of operating the facilities. The latest summary of optimisation studies undertaken to date is presented in Optimisation 2020 [51].

634 In accordance with the GRA requirements and good practice for the design of radioactive waste disposal facilities, D3100 has been designed with multiple barriers and multiple components with multiple safety functions, and with a reliance on passive safety. These are key aspects of the overall safety strategy, as outlined in Section 3. The engineered barriers and their functions are summarised in Table 5.1. In terms of post-closure safety, the main barriers and their functions are:

- The LLW containers, which limit water from contacting the waste and transporting radioactivity until they are breached. This is likely to occur hundreds of years after closure, although a few containers might be breached earlier along weaknesses or adjacent to water-flowing features.
- The grout used to condition LLW, which has a low permeability, slows water flow and provides an alkaline chemistry to retard radionuclide migration. The permeability of the grout will increase as it degrades over a period of a few

hundred to thousands of years, but the alkaline environment is expected to persist for much longer (tens of thousands of years).

- The grout backfill in the LLW vaults, which reduces overall permeability through the vaults and also provides an alkaline chemistry to retard radionuclide migration. The backfill and grouted LLW will degrade over similar timescales.
- The concrete walls of the LLW and Demolition LLW vaults, which limit groundwater ingress into the vaults. The concrete in the downstream walls may also retard radionuclide migration.
- The backfill between the vault walls and the bedrock, which has high permeability to channel flow around the vaults and prevent mounding of groundwater. The backfill may become clogged in places over time, but is likely to maintain a higher permeability compared to the vaults and waste for thousands of years.
- The lid over the vaults and the overlying cap, which reinstate the near-surface groundwater flow system and reduce releases of radioactivity upwards from the vaults. The cap is also designed to reduce the likelihood of future human intrusion. The walls, floor, waste and backfill are also designed to provide mechanical stability for the cap, thereby ensuring that it can perform for hundreds to thousands of years.
- The geosphere, which attenuates radionuclide releases and provides a physical barrier to disruption of the facilities.
- The engineered enhanced geosphere layer, which is designed to keep the water table below the ground surface and reduce upward migration of radionuclides to the terrestrial ground surface between the vaults and the cliffs.

635 The Run 5 PA models the expected degradation of the engineered barriers and erosion of the geosphere [48]. Figure 9.1 indicates where radionuclides are retained in the near-field and geosphere. Well-retarded radionuclides and short-lived radionuclides are essentially fully contained within the near-field over 100,000 years. This includes the key short-lived radionuclides making up the bulk of the inventory, such as ^{60}Co, ^{90}Sr, ^{3}H, ^{137}Cs and actinides such as ^{238}Pu and ^{241}Am. After the decay of the shorter-lived activity, there is a slight increase in overall activity in the system over tens of thousands of years owing to ingrowth of daughter isotopes. Beyond this time, activity increase through ingrowth is balanced by activity loss through decay to stable nuclides or migration out of the modelled disposal system. Releases of longer-lived activity, such as U-isotopes, gradually increase as the near-field chemical environment degrades, and the proportion of radioactivity in the geosphere and biosphere increases. However, the vast majority of the activity in the biosphere is diluted over a wide area in the marine environment and is, therefore, insignificant in terms of radiological impacts. The proportion of radioactivity in soils compared to the marine environment would not be discernible on Figure 9.1.

636 The PA calculations presented in Section 7 and illustrated in Figure 9.1 indicate that the design of D3100, coupled with the geological and hydrogeological environment at Dounreay, both now and in the future, is consistent with a robust ESC.

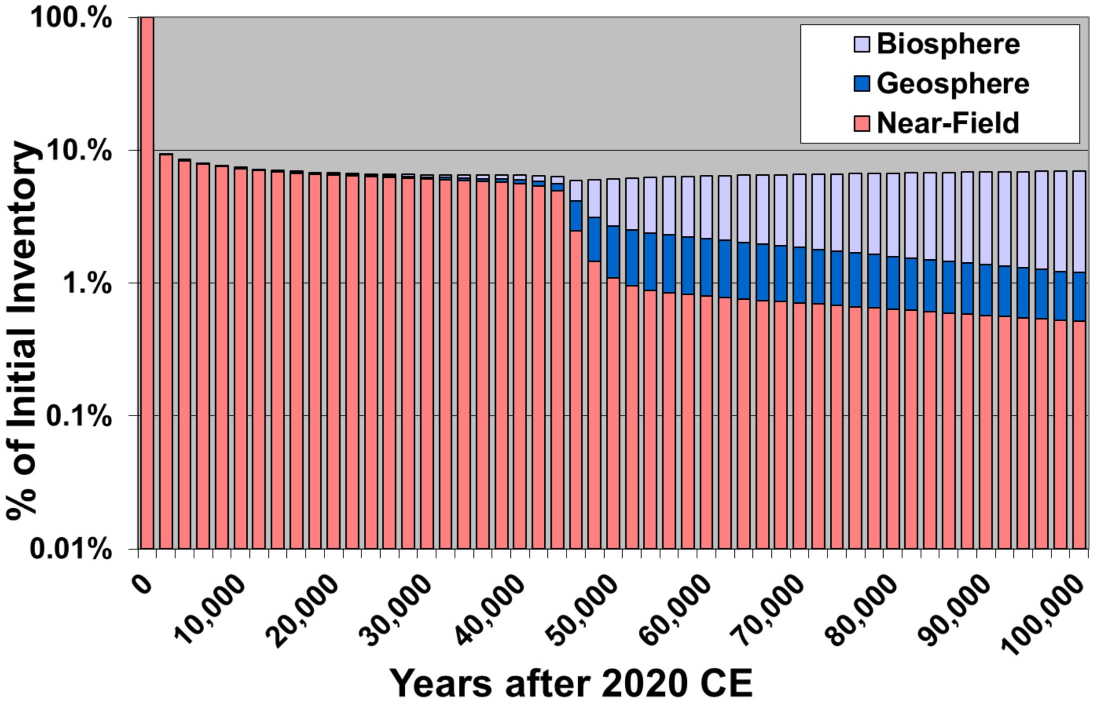

Figure 9.1: Distribution of radioactivity in the different disposal system components in the Run 5 PA over 100,000 years. The percentage is calculated on the basis of the total activity in the system component versus the total activity in the waste at 2020 CE (based on the 2020 Case B and Demolition LLW best estimate inventory).

637 The Run 5 PA uncertainty analysis considered the performance of the barriers. When considering the worst-case performance of the near-field and geosphere in terms of retardation, the results demonstrate that D3100 would still comply with regulatory safety guidance (Figure 7.19; Figure 7.21). Previous assessments have also evaluated other aspects of near-field performance, such as rapid failure of the containers and rapid degradation of the walls; however, the impact of such uncertainties was relatively small (less than one order of magnitude) (e.g. [279, ¶307]). Only the bounding "what-if" analysis in Run 5 considering poor performance (low permeability) of the enhanced geosphere and poor cap performance exceeded the GRA risk guidance level for two of the considered RPs (Crofter and Livestock Farmer, Figure 7.22). However, the probability of this case, indicated by its "what if" or bounding nature, is extremely low, as it assumes unrealistically low hydraulic conductivities (up to 40 times lower than in the reference calculation). Although the sub-soil layers of the enhanced geosphere are likely to undergo changes over time as the excavated material breaks down and it becomes more consolidated, the final bulk hydraulic conductivity value is unlikely to become lower than the bulk value for the underlying weathered bedrock, as is considered for this calculation. And yet, even in this case, the calculated risk values for the more likely receptors such as the Crofting Community RP are still well below the regulatory risk guidance level. In

regards to the individual barriers, the reference calculation shows a good compromise between achieving short-term containment and low risk, and keeping calculated risk associated with groundwater contamination in the longer term at a low level. Therefore, the multiple barriers in the D3100 design are considered to act in a complementary and balanced fashion.

638 For the LLW vaults, containment, lower groundwater contamination, and prevention of higher calculated doses in the short-term (first hundred years after closure) are provided by a low-permeability near-field. This can be achieved through the vault walls or through a low-permeability wasteform, although the latter can be expected to last longer and be more assured through its greater volume. Provision of low-permeability walls and/or LLW containers might be of secondary importance provided that the wasteform has a low permeability. However, these barriers do provide extra assurance of containment in the short-term, when activity levels in the facilities are highest. The walls and containers also have significant roles in terms of passive safety and handling during operations. Note that even if the radiological risk guidance level can be met without low-permeability walls, such walls help demonstrate compliance with the conventional hazardous waste guidance.

639 Conditioning the LLW with cement, such that it has an initial low permeability and provides a retarding medium, is the dominant engineering measure in the LLW vault design in terms of calculated dose. However, waste chemistry alone, without a low permeability, is a poor barrier in terms of containment of poorly-retarded activity and short-term contamination of groundwater.

640 Calculated doses are significantly reduced through the introduction of a vault lid and a cap to reduce vertical upward transfers from the vaults. However, a cap in isolation does not significantly reduce the horizontal fluxes of activity leaving the near-field, leading to poorer performance in terms of groundwater contamination and overall containment of activity, compared to calculations where one or more components of the vaults has an initially low permeability.

641 Calculated peak doses from the Demolition LLW vaults are exceedingly low, irrespective of whether barriers are employed. The rationale for use of barriers comes from consideration of other performance measures and other functions (e.g. operational safety, environmental impacts). The main radiological performance benefit of using a low-permeability wall is greater containment while short-lived activity decays, preventing a short-term peak in groundwater contamination. However, this also causes an increase in longer-term calculated doses, albeit only to very low levels. A cap/lid keeps calculated doses down by reducing upward discharges.

9.2 Significance of Calculated Radiological Impacts

GRA 7.3.6 and GRA 7.3.19

Where environmental safety needs to be assured over very long timescales, use multiple lines of reasoning based on a variety of evidence, leading to complementary environmental safety arguments. In the overall environmental safety case, these complementary arguments need to be brought together in a structured way.

GRA 7.2.7	To an extent appropriate to the radiological hazard presented by the waste, the environmental safety case should make use of multiple lines of reasoning based on a variety of evidence, leading to complementary environmental safety arguments. The evidence may be both qualitative and quantitative, supported where appropriate by robust numerical analyses. The reasoning and assumptions should be clear and the evidence supporting them traceable.
GRA 7.3.7(a)	Examples of environmental safety indicators that might be used to strengthen the environmental safety case include radiation dose, radionuclide flux, radionuclide travel times, environmental concentration and radiotoxicity.
GRA 7.3.7(b)	Where the radiological hazard presented by the waste warrants it, provide a wide range of information, for example: - assessments of radionuclide release characteristics from the waste and from the various barriers that make up the disposal system; - assessments of the concentrations in the accessible environment of radionuclides released from the disposal system and comparison of these with naturally occurring levels of radioactivity in the environment; - where appropriate, assessment of collective radiological impact (as a measure of how widespread any significant increase in risk may be as a result of radioactivity released into the accessible environment); - unifying statements that aim to place in context the different items of information that contribute to assuring environmental safety.

642 As well as the examples of environmental safety indicators given in the GRA, there have been numerous international studies of alternative "safety indicators" to illustrate the safety of radioactive waste disposal facilities (e.g. [353]). These alternative indicators include doses from naturally-occurring radiation, fluxes of radioactivity and natural environmental concentrations.

9.2.1 Comparison to background radiation levels

643 The figures in Section 7 include a line showing the average dose (or equivalent risk) from naturally occurring radiation in the UK. The main sources of radiation giving rise to everyday doses are illustrated in Figure 9.2. In some parts of the UK, doses from naturally occurring radiation are higher owing to localised higher concentrations of radionuclides in rocks and soil and increased emissions of radon; for example, the average dose in Cornwall is around 7.3 mSv y^{-1} from naturally occurring radiation [312, Fig.12]. The average dose from naturally occurring radiation in the Highlands is around the same as the UK average of 2.6 mSv y^{-1} [312, Fig.12].

644 Figure 9.2 shows that the post-control regulatory risk guidance level for radioactive waste disposal facilities is equivalent to a received dose (i.e. probability of exposure of one) roughly one hundredth of the UK average background dose from naturally occurring radiation (0.02 mSv y^{-1} compared to 2.6 mSv y^{-1}). Therefore, the calculated doses from D3100, which are below the regulatory guidance level, are not significant compared to doses from natural sources of radiation. This is illustrated further by Figure 9.3, showing that adding the calculated peak annual dose that the Crofter RP might receive from D3100 (Figure 7.10) to the average background dose from naturally occurring radiation in the Highlands makes no discernible difference to the total dose.

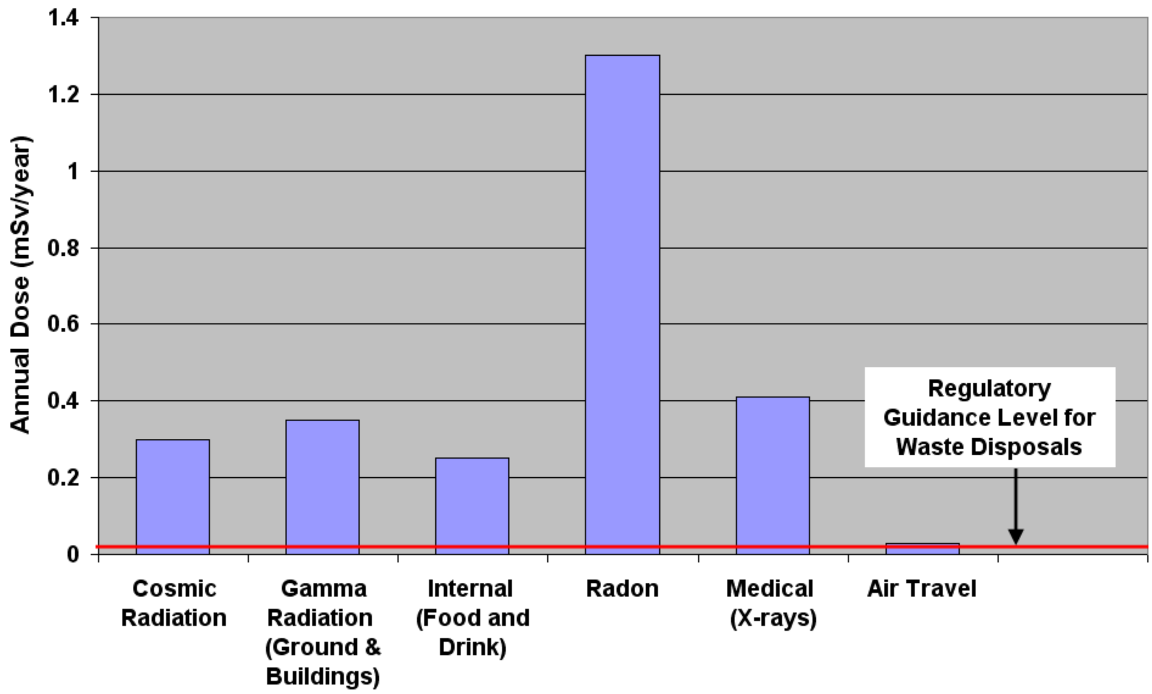

Figure 9.2: Average annual doses from natural and medical sources of radiation in the UK [312]. Regulatory dose guidance level of 0.02 mSv y^{-1} is calculated from the GRA risk guidance level assuming a probability of exposure of one.

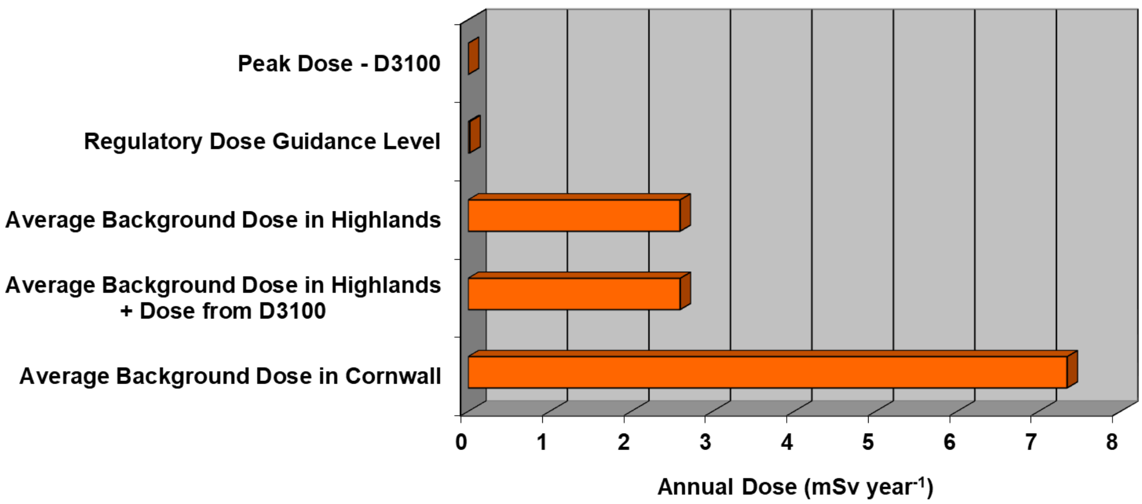

Figure 9.3: Illustration of the negligible difference the calculated peak annual dose (to the Crofter RP) from D3100 would make to the average annual dose received from background radiation in the Scottish Highlands (data from [312, Fig.12]). Peak dose and regulatory dose guidance level assuming a probability of exposure of one.

9.2.2 Comparison to present-day discharges

645 Radionuclide releases from D3100 and the resulting radionuclide concentrations over time in various parts of the environment are illustrated in Figure 7.14 and Figure 7.13, respectively.

646 Figure 9.4 compares the actual annual discharge of alpha activity in liquids from the Dounreay licensed site between 1957 and 2019 [354; 355] with the Run 5 calculated peak annual release of alpha activity and the total calculated cumulative release of alpha activity over 100,000 years from D3100 into the surrounding environment. However, whilst this is a useful comparison, it is noted that the discharge locations are different: the authorised discharge limit applies to discharges from a pipeline into the sea, whereas D3100 is modelled as releasing activity to the rock and soils surrounding the facilities. Nonetheless, the activity released from the facilities gradually migrates towards the sea through groundwater and surface flow. Initially, the calculated flow of activity from the facilities into the surroundings is larger than the activity flow into the sea. However, as the activity migrates through the system, an equilibrium is slowly established and the activity flow into the sea from the land mirrors the activity flow from the facilities.

647 Figure 9.4 shows that the calculated peak annual release of alpha activity from D3100 into the general environment and, more specifically, into the sea, is considerably less than the historic annual liquid discharges into the sea from the Dounreay licensed site, which, in turn, are well below the discharge limits permitted at the time. The permitted discharge limits and annual discharges have reduced further since 2000 as the site has transitioned from operations to decommissioning (the aqueous alpha activity discharge limit is currently 3.4×10^9 Bq y^{-1} [45, Tab.1]), and the peak annual release from D3100 is now comparable to the site annual alpha activity discharge. However, even if the total cumulative release from the facilities over 100,000 years is considered, the activity release is comparable to actual licensed site discharges that have occurred historically in one year.

648 Figure 9.5 shows the same conclusions are even more pronounced for beta and gamma activity. The actual discharges shown for the Dounreay licensed site exclude a contribution from tritium (controlled and reported separately), and the calculated releases from D3100 are, therefore, even further below the actual site discharges than indicated in Figure 9.5. Excluding permitted ^{3}H, ^{137}Cs and ^{90}Sr discharges, the aqueous non-alpha activity discharge limit is currently 4.8×10^{10} Bq y^{-1} [45, Tab.1], more than two orders of magnitude greater than the predicted peak annual release from D3100.

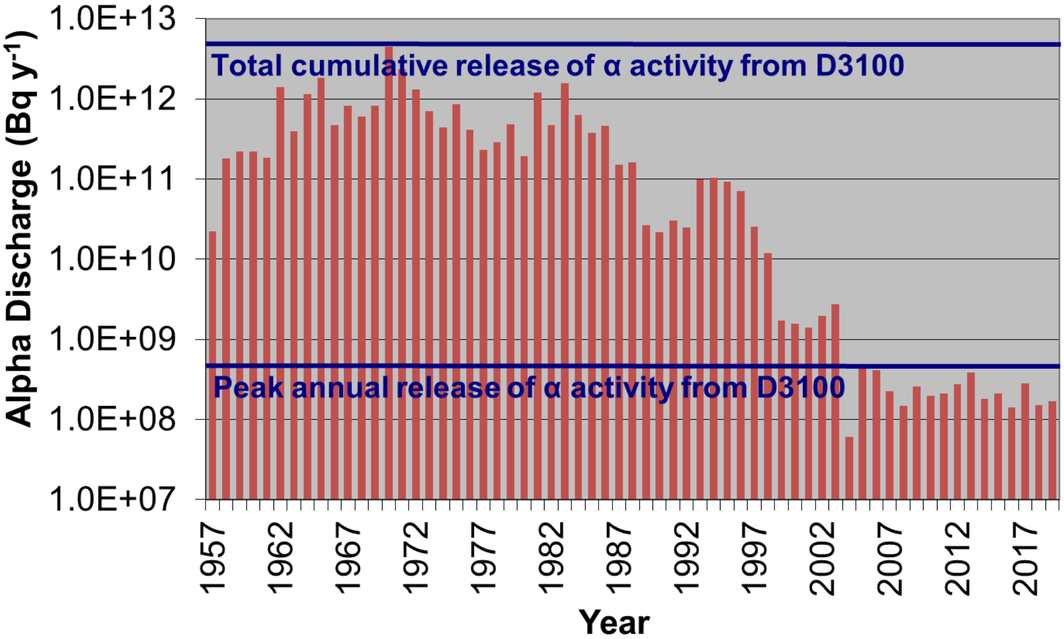

Figure 9.4: Calculated peak annual release of alpha activity from D3100 to land (and eventually the sea), and total cumulative release of alpha activity over 100,000 years (in Bq rather than Bq y^{-1}), compared to actual liquid alpha activity discharges from the Dounreay licensed site to sea from 1957 to 2019 (in compliance with permitted levels) [354; 355].

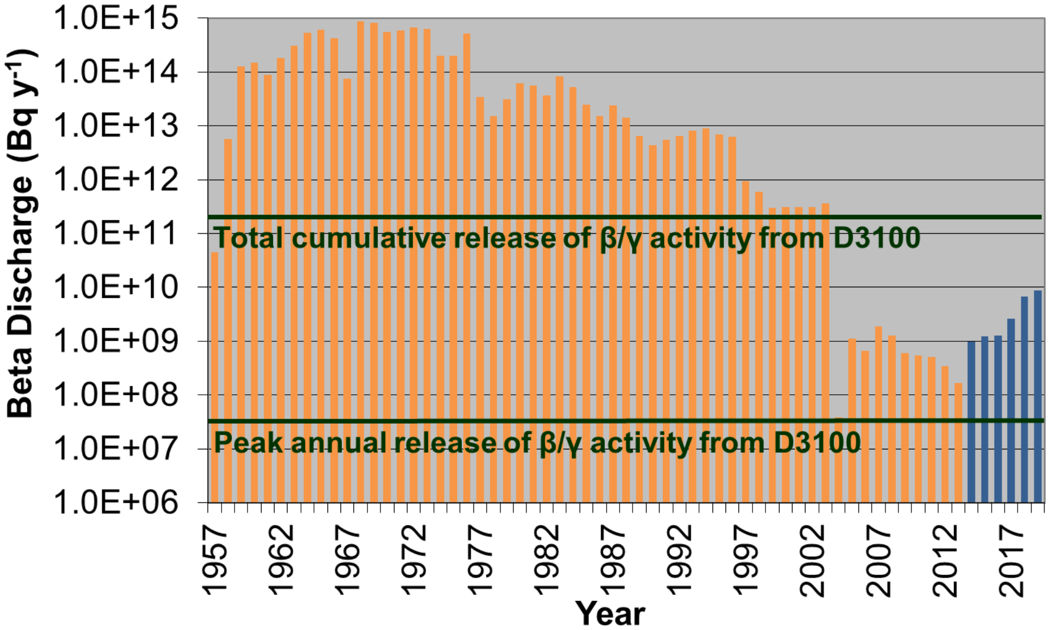

Figure 9.5: Calculated peak annual release of total beta/gamma activity from D3100 to land (and eventually the sea), and total cumulative release of beta/gamma activity over 100,000 years (in Bq rather than Bq y^{-1}), compared to actual liquid beta activity discharges (excluding tritium) from the Dounreay licensed site to sea from 1957 to 2019 (in compliance with permitted levels) [354; 355]. The method by which beta/gamma activity is measured changed in 2014 (indicated by blue bars).

649 Monitoring required by SEPA [313, §3.1] indicates that the potential radionuclide transport pathways associated with the marine environment at Dounreay currently lead to only low doses. The pathways considered are exposure of consumers from locally collected fish and shellfish, which includes external exposure from occupancy of local beaches. The monitoring results are consistent with assessments undertaken by DSRL and the Food Standards Agency (FSA) in relation to proposed changes to the annual authorised discharge limits in 2010 [356; 357; 358]. Although releases from D3100 will not enter the marine environment at the same location as the current licensed site discharges (at the coastline for D3100 rather than 600 m offshore for the Dounreay site) and the mix of radionuclides in the releases will be different to the mix in the site discharges, calculated releases are considerably lower than authorised site discharges, which have negligible impact. The present-day situation helps to build confidence that the low anticipated releases from D3100 will have negligible impact on the environment in the future.

9.2.3 Comparison to present-day radioactive concentrations

650 Owing to the low releases of radioactivity, calculated concentrations and fluxes of radionuclides in the Dounreay environment resulting from D3100 are much lower than present-day measured concentrations (Table 9.1). The present-day concentrations are partly naturally occurring and partly related to past discharges from the Dounreay licensed site and elsewhere.

651 The concentrations in Table 9.1 are well below the deliberately cautious Generalised Derived Limits (GDLs) set by the UK regulatory authorities that would correspond to a dose of 1 mSv y^{-1} based on simple assessment models [359, Tab.43]. For example, the GDL for ^{90}Sr in grass is 2,000 Bq kg^{-1} dry weight. Similarly, the soil and rock concentrations are well below the European clearance levels for radioactive materials based on a dose threshold of 10 μSv y^{-1} [360, Tab.1]. Again, for the example of ^{90}Sr, material is defined as radioactive if it has a concentration of ^{90}Sr in excess of 1 Bq g^{-1} (1,000 Bq kg^{-1}). This same concentration is now specified as an exemption and clearance level in the new EC BSS [80] and as radioactive material in EASR 18 [34, Sch.8, Tab.2]. Therefore, the observation that the calculated concentrations in the environment through releases from D3100 are well below the clearance levels remains valid.

Table 9.1: Comparison of present-day radionuclide fluxes and concentrations in the Dounreay environment [315] with peak fluxes and concentrations calculated to result from D3100 [48].

Location	Measure (units)	D3100 Run 5 PA Peak	Measured Present-Day Value
Dounreay/Caithness	Alpha activity flux peak (Bq y^{-1})	3.8E+08	6.3E+08 [1]
Dounreay/Caithness	Beta/gamma activity flux (Bq y^{-1})	2.3E+07	6.3E+08 [2]

Location	Measure (units)	D3100 Run 5 PA Peak	Measured Present-Day Value
Dounreay Soil	^{238}U activity peak (Bq kg^{-1})	9.4E-06	36 to 65 [4] (38) [5]
Dounreay Grass	^{90}Sr activity peak (Bq kg^{-1})	1.9E-07	0.17 [5]
Dounreay Grass	^{234}U activity peak (Bq kg^{-1})	1.1E-05	0.13 *max* [5]
Crabs (Dounreay Pipeline)	^{99}Tc activity peak (Bq kg^{-1})	2.2E-04	0.62 [5]
Crabs (Dounreay Pipeline)	^{239}Pu+^{240}Pu activity peak (Bq kg^{-1})	1.5E-04	0.86 [5]

1 U and Th chain flux through present-day cliff erosion and groundwater discharge at Dounreay [315, Tab.3.4].
2 Natural ^{40}K flux through cliff erosion and groundwater discharge at Dounreay [315, Tab.3.4].
3 Through present-day cliff erosion and groundwater discharge at Dounreay [315, Tab.3.4].
4 Values in Dounreay soils [315, Tab.4.1].
5 Arithmetic sample means from RIFE-24 [313, Tab.3.2(a)], unless stated as maximum.

9.2.4 Overall performance of D3100

652 Paragraph 461 summarised that D3100 will contain most of the radionuclides placed in the facilities until they radioactively decay. The majority of the Case B LLW to be disposed of at Dounreay derives from short-lived radionuclides (i.e. radionuclides with half-lives shorter than approximately 30 years). This radioactivity will decay to insignificant levels in a few hundred years. In 300 years, roughly 90% of the initial radioactivity disposed of will have decayed, and the average radioactivity of the wastes will be comparable to that currently found naturally in soils around the Dounreay site (albeit comprised of a different mix of radionuclides with different radiotoxicities) (Figure 9.6). The non-radioactive content of the wastes is already at a low level. Therefore, after a few hundred years, the facilities represent a very low hazard. Overall, less than 1% of the total initial beta/gamma activity is released. An even smaller proportion of the activity reaches the biosphere. Therefore, D3100 achieves its performance objective of containing and isolating the radioactivity.

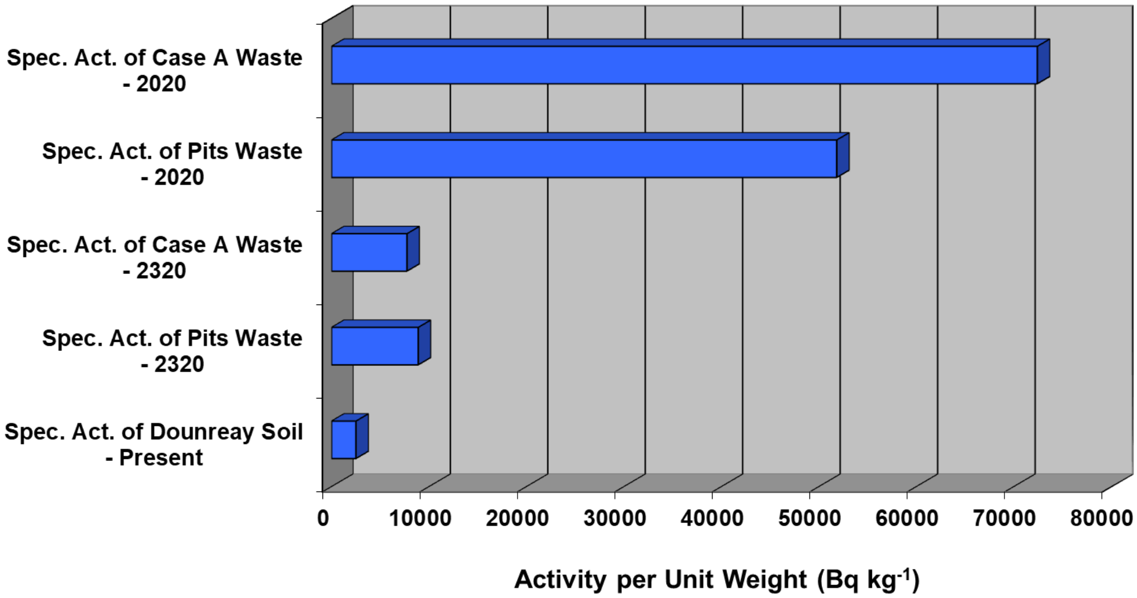

Figure 9.6: Chart showing the radioactive decay of the specific activity of packaged 2020 Case A and LLW Pits waste, compared to the naturally occurring specific activity in Dounreay soil. Note that the figure has been calculated using the Run 5 PA model and so very short-lived activity (half-life less than 5 years) is not included.

653 D3100 has been designed taking account of good practice worldwide in operational facilities for LLW disposal. Given the high degree of engineering to ensure short-term containment and the low hazard after a few hundred years of radioactive decay, it follows that the facilities demonstrate excellent performance with regard to the stringent radiological safety requirements.

9.2.5 Continued safety beyond the quantitative assessment timescales

654 The quantitative D3100 project PA assessment has been run to the time of peak doses, and the implications of the potential disruption of the facilities before and after peak doses are reached have been assessed (Figure 7.10, Figure 7.16, and Figure 7.17). Therefore, beyond the timescales of the quantitative assessment, doses will not exceed those presented in Figure 7.10, Figure 7.16, and Figure 7.17, and the continued safety of the facilities is assured.

9.3 Confidence in the Safety Assessment

GRA 7.2.9	The environmental safety case should describe the arguments for having confidence in the case including, for example, reference to: - the quality and robustness of the quantitative safety assessment and consideration of uncertainty; - the quality, robustness and relevance of the other arguments and evidence presented; - the developer/operator's environmental safety culture and the breadth and depth of expertise and experience of individuals involved in activities supporting the ESC; - the main features of the developer/operator's management system, such as planning and control of work, the use of sound science and good engineering practice, record-keeping, quality management and peer review.
GRA 7.2.4	The environmental safety case should explain how uncertainties have been considered and will be managed in the future and demonstrate that there can be confidence in the environmental safety case notwithstanding the uncertainties that remain. It should also demonstrate that potential biases and their effects on the environmental safety case have been identified and eliminated or minimised.
GRA 6.2.26	All work that supports the environmental safety case needs to apply sound science. Make informed judgements about the quality of the science being applied and make sure that timely scientific investigations are carried out to remedy any deficiencies in understanding of particular relevance. Maintain awareness of scientific developments, both within and outside the UK, that may have a bearing on the environmental safety case for the facility.
GRA 6.2.40	Where appropriate, use peer review to supplement other approaches to quality management. The rigour with which peer review is carried out needs to be proportionate to the significance of the work being reviewed to the environmental safety case. The peer review process must not be inappropriately curtailed. There needs to be a clear-cut stage in which the originators of the technical work respond to the reviewers' comments. Provide the comments made by peer reviewers and the responses to those comments to the regulators.
GRA 7.3.23	Carry out a systematic programme of work to build confidence in modelling. This will include interpreting raw data and developing and testing conceptual, mathematical and computational models. The measures adopted in a confidence-building programme should include: - systematic approaches to model building and consideration of alternative models; - iteration between model building, quantitative assessments and data collection; - good communication between modellers (including those developing and using models), suppliers of data (including those planning research or data collection and those actually making observations) and those using modelling results; - continuing peer review of model development; - rigorous quality assurance of all modelling activities and associated data handling, including controls over changes to models and data and a detailed audit trail.

GRA 7.3.26	Provide the basis for the judgements to end the programme of building confidence in the modelling, area by area.
GRA 7.3.29	As far as possible, use standard approaches to establish the environmental safety case, thus relying on appropriate expert judgement in gathering and interpreting evidence and applying it to construct and use the qualitative and quantitative models.

655 Consistent with the IAEA guidance [24], confidence in the D3100 radiological safety assessment, or PA, is provided by a variety of means, including:

- application of sound science;
- adoption of a formal PA methodology requiring structured consideration of uncertainty and good communication;
- adopting conservative modelling assumptions where necessary to address uncertainty;
- parallel development of independent sets of PA models for Run 1, comparison between Run 1 and Runs 2, 3, 4 and 5, and comparison with PA calculations conducted for the LLWR;
- verification of the computer models;
- validation of the PA models through site characterisation, experiments and analogue studies; and
- peer review and regulatory review of the PA and the ESC.

656 Each of these means of assurance is discussed below.

9.3.1 Application of sound science

657 The application of sound science has been achieved through production of the ESC itself and its many supporting documents, all of which have been checked through peer review. Since the start of the D3100 project, DSRL has used internationally experienced contractors to undertake and review the D3100 project PA and issues of the ESC. The contractors have worked on many national and international radioactive waste management programmes. In developing the Run 1 PA, the contractors undertook a review of the international literature, identifying the most relevant and robust data and models on which to base the PA (e.g. [177; 190; 191; 141]). This process looked at safety assessments undertaken for many other projects worldwide, and the data selected for the D3100 project PA, therefore, represent a consolidation of expert judgement across many projects (see [19, ¶7.3.29], which describes such judgements as "held in common"). Further, the design of D3100 has adopted established and well understood components and technologies, for which behavioural models and PA data are established in a number of programmes.

658 Through work by contractors for other programmes, implementation of the D3100 project monitoring programme on waste management, liaison between DSRL and other waste management programmes (e.g. that at the LLWR), and interfacing with other assessment programmes at Dounreay (e.g. the Shaft and site end-state), the

D3100 project maintains an awareness of scientific developments in LLW management and PA, both within and outside the UK. Knowledge of such developments feeds into PA and optimisation analyses, including review of past decisions, and planning for future iterations of the PA.

9.3.2 Formal PA methodology and treatment of uncertainty

659 In accordance with the application of sound science, all of the iterations of the D3100 project PA have been based on a formal development process that conforms to internationally accepted PA methodology (Figure 7.1; [64]). The formalised methodology means that all necessary aspects of the assessment are covered and requires a structured treatment of uncertainty. The use of a FEP list and formal FEP analysis to support scenario development ensure that all features, events and processes have been considered. FEP analysis also acts as a mechanism for communication between modellers. Some differences between the two Run 1 PA developments arose from different FEP screening decisions. However, these differences were reviewed and consolidated in Run 2. The iterative FEP analysis and the bounding approach to the modelling of events such as inadvertent human intrusion mean that a comprehensive set of potential futures has been covered. In Runs 2, 3, 4 and 5, the PA modelling and supporting modelling have been undertaken within the same team, ensuring that good interfaces have existed between the different modelling exercises.

660 The systematic treatment of uncertainty in the D3100 project PA is consistent with the requirements of the GRA [19] and is described in paragraphs 357 to 362. Section 7.7.3 summarises the uncertainty analyses undertaken as part of the D3100 project PA. These analyses have examined the potential consequences of recognised variability and uncertainty in the parameter values and models on which the PA calculations are based. The analyses show that, even allowing for unexpectedly poor performance of the engineered and natural barriers in the disposal system, the D3100 disposal facilities provide a level of safety consistent with the regulatory radiological protection guidance [19]. None of the uncertainties threaten the ESC. However, DSRL is committed to building confidence, and ongoing review of the D3100 project register of uncertainties [361; 362; 363] focuses on reducing uncertainties in the assessment results where justified by an analysis of cost versus the importance of the uncertainty and the likelihood of success in reducing it.

9.3.3 Conservatism

661 The Run 1 PA calculations were conducted primarily to establish whether a LLW disposal facility at Dounreay would comply with the requirements of the GRA. On this basis, both PA contractors (EQ and GSL) adopted conservative modelling assumptions that could be used to illustrate the potentially most significant consequences of a given pathway or combination of pathways. In the later iterations of the D3100 project PA, realistic assumptions have been used where possible, but conservative or cautious assumptions have been used where uncertainties and complexities preclude a more realistic approach [48]. For example, cautious assumptions have been adopted regarding releases of radioactivity into infiltrating groundwater (rapid resaturation/failure of containers, instantaneous dissolution of

radionuclides), migration of radioactive gases (instant release, no attenuation of radon in the soil), behaviour of RPs (deriving many foodstuffs from the small area of land potentially contaminated by releases from the facilities), and redistribution of wastes during inadvertent disruption of the facilities. While it is not certain that the combination of cautious assumptions in the PAs lead to pessimistic results in all cases, it is likely that more realistic modelling would result in lower calculated impacts, perhaps by several orders of magnitude, compared to those presented in Section 7, which already show compliance with the regulatory safety guidance.

9.3.4 Comparison of PA models

662 Under Stage 1 of the D3100 project, UKAEA recognised the degree and significance of uncertainties in PA models over the long assessment timescales (tens of thousands of years) and saw value in commissioning two separate PA studies to help provide assurance that the Run 1 PA covered all issues and that the conclusions were robust. The two studies by EQ and GSL were compared by a joint PA team [275]. The basis for the conduct and comparison of the two assessments is illustrated in Figure 9.7.

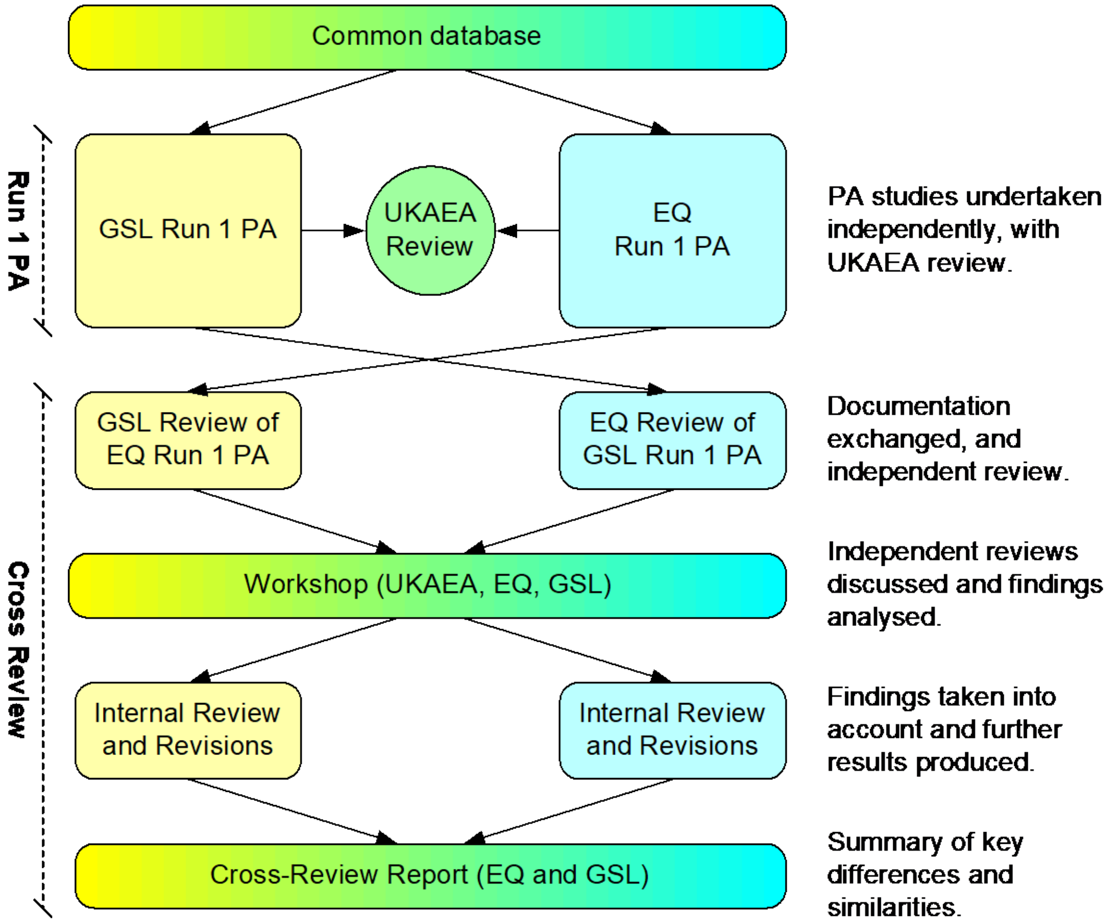

Figure 9.7: Cross-review of the two independent developments of the Run 1 PA [275, Fig.1.1].

663 Although the studies were undertaken independently, both assessments used a common database as a source of input data to promote a meaningful comparison of

the results. Both consultants undertook independent reviews of each other's documentation and results. A workshop with EQ, GSL and UKAEA staff was then used to discuss the reviews, to take account of the observations, and to jointly identify the main issues arising from the reviews. Revised results were then calculated to take account of the reviews and to provide further information for the comparison.

664 Both studies suggested that a case for the long-term radiological safety of the LLW options could be made. There were many similarities in the two studies, reflecting the formal PA methodologies adopted by both consultants and the use of a common source database. Nevertheless, there were some important differences between the studies arising from the different scenarios and the different models developed and the assumptions that underpinned them. These differences were taken into account in the development of the Run 2 PA.

665 In the cross-review, the differences in the results from the two assessments were all traced to, and explained by, differences in modelling assumptions and/or parameter values [275]. That the results from the two separate assessments, despite their differences, showed compliance with the regulatory guidance levels adds confidence to the overall conclusion that a case can be made for the long-term radiological safety of D3100.

666 Shortly after the completion of the Run 1 PA, British Nuclear Fuels Ltd (BNFL) submitted a Post-Closure Safety Case (PCSC) for the LLWR [364]. The 2002 BNFL PCSC contained a PA (the Post-Closure Radiological Risk Assessment [PCRSA]) for concrete vaults at the LLWR that are similar in design to D3100. A comparison was made between the BNFL PCRSA and the Run 1 PA [365]. Allowing for differences related to design, inventory and geological setting, the PA results for Vault 8 at the LLWR and the Run 1 PA results for D3100 were similar, in terms of both dose/conditional risk and key contributing radionuclides. This provided additional assurance that the Run 1 PA results are robust.

667 In 2011, an ESC was prepared for the LLWR in compliance with the updated GRA [366]. The LLWR and D3100 ESCs address the same regulatory guidance and DSRL commissioned a comparison between the 2011 ESC for the LLWR and the D3100 ESC 2010 Issue 1 [367]. Again, allowing for differences related to design, inventory, and geological setting, the ESCs for the LLWR and D3100 are similar, in terms of both approach and safety arguments. Assessment results are similar in terms of exposure pathways and key radionuclides. This provides assurance that the D3100 ESC and the supporting PA results are robust.

668 Differences between the iterations of the D3100 project PA relate principally to changes in the inventory, location of the facilities, changes in the parameterisation of the near-field, and development of the hydrogeological conceptual model. However, in each iteration of the PA, the same radionuclides contribute to the peak dose, the peak dose is related to release of alpha activity over thousands to tens of thousands of years, and a key exposure pathway is consumption of livestock reared on contaminated grazing. All of the iterations of the D3100 project PA show that the D3100 disposal facilities meet the regulatory safety guidance levels.

9.3.5 Verification of PA computer models

669 Consistent with the use of sound science, the iterations of the D3100 project PA have used internationally recognised computer software. GoldSim-RT, used in the D3100 PA since 2006, is a world-class modelling tool that has been used elsewhere to conduct assessments of radioactive waste disposal facilities in the UK (e.g. the LLWR and the NDA geological disposal facility for higher activity radioactive wastes), the US (Yucca Mountain), Spain (ENRESA), France (ANDRA) and Japan (NUMO). Therefore, GoldSim-RT has been used for the D3100 project PA with a high degree of assurance that it is fit for purpose. Where computational routines have been developed specifically for the D3100 project PA calculations, verification exercises have been undertaken (e.g. see [279, App.1; 278, App.2; 48, App.A]). Combined with the comparison of calculations from other PAs (see above), these verification exercises provide confidence that the PA computer models accurately implement the appropriate mathematical models described in the PA documentation.

9.3.6 Validation of PA models

670 Validation of PA models (i.e. testing that the models are appropriate representations of the disposal system and its evolution) is a key aim of safety assessment programmes worldwide. PA models as a whole cannot be validated directly owing to the modelling timescales involved. However, conceptual models on which PAs are based can be validated, and the values of model parameters employed can be validated. Models and parameters are often tested through site characterisation studies, experimental investigations and comparison with observations from analogues. The use of both engineering and natural analogues to support the assumptions made in the PA calculations has been reviewed by DSRL [315; 354; 368].

671 The D3100 project PA model for the marine environment has been developed using data on water and sediment fluxes from more detailed models [292]. Validation analysis [292], based on monitoring of Dounreay discharges and measured concentrations of radioactivity in the marine environment, suggests that the marine model used in the PA may slightly under-predict dissolved radionuclide concentrations in marine waters. However, the Dounreay marine monitoring data may be skewed by the effects of Sellafield marine discharges. Notwithstanding this issue, the marine pathway is not a significant contributor to total calculated dose in the D3100 project PA, and this conclusion would not be affected by a one-order or two-order increase in marine radionuclide concentrations.

672 In the D3100 project PA, the near-field chemical environment of D3100 is envisaged as evolving in stages according to expected changes in the condition of the cement and pH (see paragraph 403). Inflowing surface or groundwaters at near-neutral pH are conditioned in the LLW vaults to an initially high pH by reaction with the cement walls and wasteform and, after specified periods, there is a drop back to lower, more neutral pH values. The minimum, best estimate and maximum values assumed for the duration of the three pH stages considered are as follows [177, Tab.2.4]:

- pH 13 stage: 100; 500; and 5,000 years.
- pH 12.5 stage: 1,000; 5,000; and 50,000 years.

- pH 12.5 to 10.5 stage: 10,000; 40,000; and 500,000 years.

673 Although analogue information was not explicitly used to support the above periods, the choices fit in roughly with the timescales based on evidence from chemical modelling and cement analogue studies, as described below. The minimum duration of 100 years for the first hyperalkaline stage fits in broadly with results drawn from studies of modern industrial cement [368]. The best estimate of 500 years for the first stage is consistent with the evidence from the analogue of cement in Hadrian's Wall, albeit erring on the side of caution [368, ¶126]. The maximum duration for the second pH stage accords with the timing of the hydration of cementitious rocks in the Maqarin area [368, ¶127].

674 A study of radionuclide migration around the historical LLW Pits Complex has been undertaken by DSRL in response to a regulatory action imposed by SEPA. The findings of this study are consistent with the assumptions in the D3100 project PA models regarding the migration behaviour of actinides in the geosphere. Most notably, there is evidence for migration of uranium and strontium, consistent with the assumption of smaller distribution coefficients between solid and liquid phases for these radionuclides in the PA [253].

675 Further use of analogue information to build confidence in the D3100 project PA will continue to be evaluated as part of review of the project's register of uncertainties.

9.3.7 Peer review

676 For Run 1, UKAEA considered that the comparison of the separate PA models by each PA contractor provided an appropriate level of peer review. The Run 2 PA was formally peer reviewed ([333; 334]) and reviewed on behalf of SEPA [277]. The changes from the Run 2 PA to Run 3 were not significant, and were generally made in response to the review comments on Run 2, so additional peer review was not undertaken. The Run 4 PA was peer reviewed, focussing on the substantive changes to the human intrusion assessment [369; 370] and peer review of the Run 5 PA has also been undertaken [371; 372]. The geological interpretation has been peer reviewed [222]. The 2010 PCCSA was peer reviewed [373] and reviewed on behalf of SEPA [374], and CSA 2020 has also been peer reviewed [375; 376; 377]. Previous issues of this ESC have also been peer reviewed [378; 379; 380; 381], as well as the current issue [382; 383]. DSRL is committed to continuing the peer review of the PA and other key components of the ESC according to DSRL quality assurance procedures. Peer review comments are considered in planning future work and future issues of the ESC documentation.

9.3.8 Further confidence building

677 DSRL maintains a register of uncertainties [362; 363] that includes consideration of activities to build confidence in the D3100 project PA models and parameter values. Periodic review of the register considers the benefits that possible site characterisation, experimental and analogue studies could have in building confidence in the models and parameter values. Review of the register is undertaken in parallel with review of the ESC, both of which inform activities required to maintain

and improve the D3100 disposal facilities. This exercise is described in the ESC Management Plan [384].

FP.10 Periodically review and update the D3100 project's Register of Uncertainties.

10 MONITORING

678 For the purposes of this ESC, monitoring is defined as continuous or periodic observations and measurements of engineering, environmental or radiological parameters to help evaluate the behaviour of the disposal system or the impacts of the disposal facility and its operation on the environment. This definition is consistent with international guidance [25] and the GRA [19]. Therefore, monitoring does not cover site investigation activities or one-off measurements, except insofar as such activities are used to define the baseline for monitoring. Characterisation activities and measurements are covered under site characterisation planning in Section 6 (see paragraph 164). The SCP for D3100 has been developed as necessary over time to include the activities needed to establish the monitoring baseline for planned D3100 monitoring.

679 This section of the ESC addresses the detailed requirements in the GRA related to monitoring. Monitoring across the Dounreay licensed site, and on and around the D3100 area, that was used to help establish the environmental baseline for the planning application for D3100 is first considered, followed by consideration of monitoring undertaken for the D3100 project. This includes programmes that are required throughout the period of authorisation. It is important to recognise that assessed monitoring needs will continue to be specified in detail as the D3100 project evolves. In particular, the post-closure monitoring objectives will be carefully considered and evaluated with respect to stakeholder concerns and the potential cost benefits before agreements are made to pursue any monitoring programmes. Monitoring programmes implemented during the post-closure period are likely to be focused on stakeholder reassurance. Any post-closure monitoring programmes will be specified such that there is no potential to compromise the environmental safety of the facilities.

GRA 6.4.31	**Requirement R14: Monitoring.** In support of the environmental safety case, the developer/operator of a disposal facility for solid radioactive waste should carry out a programme to monitor for changes caused by construction, operation and closure of the facility.
GRA 6.4.32	Establish a reasoned and proportionate approach to a programme for monitoring the site and facility. This monitoring should provide data during the period of authorisation to ensure that the facility is operating within the parameters set out in the environmental safety case. However, the monitoring must not itself compromise the environmental safety of the facility.
GRA 6.4.33	Carry out monitoring during the investigation and pre-construction stages to provide a baseline for monitoring at later stages. The same measurements may form part of the site investigation programme. They should include measurements of pre-existing radioactivity in appropriate media, together with geological, physical and chemical parameters which are relevant to environmental safety and which might change as a result of construction and waste emplacement (for example groundwater properties such as pressures, flows and chemical composition).

GRA 6.4.34	Undertake radiological monitoring and assessment during the period of authorisation to provide evidence of compliance with authorised discharge limits and assurance of radiological protection of members of the public. In addition, during the construction stage and the period of authorisation, monitor non-radiological parameters to confirm understanding of the effects that construction, operation and closure of the facility have on the characteristics of the site. In particular, demonstrate that changes in, and evolution of, the parameters monitored are consistent with the environmental safety case.
GRA 6.4.36	The monitoring programme should clearly to set out the levels of specific contaminants that will trigger action. It should include an action plan to deal with possible contamination from the facility and an approach to confirming any apparently positive results to avoid inappropriate action being taken in the event of a false positive observation.
GRA 6.4.37	Assurance of environmental safety must not depend on monitoring or surveillance after the declared end of the period of authorisation. Subsequent monitoring that the developer/operator may wish to include is not ruled out, provided it does not produce an unacceptable effect on the environmental safety case.
GRA 6.3.5	During the period of authorisation, have a management system in place that provides a level of control on operational discharges that is proportionate to the hazard. In accordance with the authorisation: - monitor and assess radioactive discharges from the facility and levels of radioactivity in the environment; - have plans for action if monitoring suggests an unexpected release from the facility; - put into action remediation plans if any adverse anomalies are identified as a consequence of monitoring; - carry out dose assessments based on the levels of radioactive discharge permitted by the authorisation (prospective assessments) and assessments based on the levels of radioactivity measured in the environment (retrospective assessments); - report this information to the regulator.
GRA 7.2.18(b)	The environmental safety case may help to guide the monitoring of discharges for compliance with the authorisation, and the environmental monitoring programme for the site and the surrounding area.

10.1 Monitoring – Dounreay Licensed Site and Surrounds

680 In compliance with the authorisation by SEPA of discharges from the Dounreay site, DSRL has carried out monitoring of radioactivity in the terrestrial and marine environments at, and around, Dounreay for many years. During the initial development of the D3100 PA, the data from the site monitoring programmes (at that point covering the period up to 2005) were compiled into a database by the D3100 project to assist in evaluating the potential impacts of the facilities [354]. The database provided the following information:

- data value;

- data type (i.e. aqueous discharge, gaseous discharge, or environmental concentration);
- date (all data are held at year-level only);
- location information for concentration measurements;
- radionuclide or activity type;
- environmental media for concentration measurements (e.g. soil, seawater, fish, mussels);
- data source and details;
- quality indicator; and
- any other relevant information.

681 The data in the database are sufficiently current for the purpose of considering the potential impacts of D3100. Therefore, the database has not been updated beyond 2005. However, monitoring of radioactivity in the environment at Dounreay continues at the present day under the Dounreay Site Environmental Monitoring Programme (EMProg), with older data held within the EMPROG record management system (a series of spreadsheets) and data obtained post-2012 held in the IMAGES database. The EMProg fulfils the wider environment monitoring requirements for the permits for both D3100 and the Dounreay site and this is discussed further in the next section.

682 Several specific radiological surveys of the Dounreay licensed site and surroundings have also been undertaken at specific times in the past, and these provide data of relevance to characterising the D3100 area. For example, during 1998, UKAEA commissioned an aerial radiological survey of the land up to around 8 km from Dounreay to complement and extend the existing environmental monitoring programme (Figure 10.1; [385]).

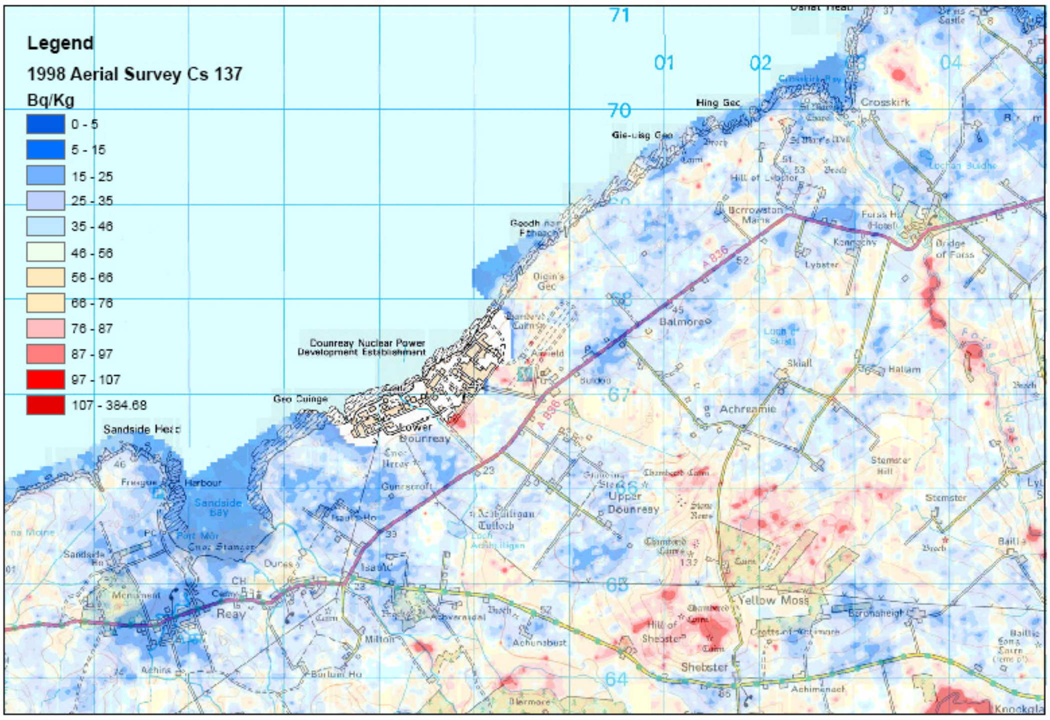

Figure 10.1: District-scale map of surface ^{137}Cs activities around Dounreay determined by an aerial gamma radiation survey [385].

683 In addition to radiological monitoring, data on other environmental features at the Dounreay site have also been collected in the past, for example as part of the Site-Wide Environmental Study [386]. These data were used to support the Environmental Impact Assessment for D3100 [16], and were used to evaluate impacts of construction and operation of the facilities. The data cover, *inter alia*:

- ecology (covering flora and fauna);
- noise (including on-site and off-site emissions and transport noise);
- air quality (including dust and particles, but excluding radioactivity);
- socio-economic conditions (covering population statistics and characteristics, industry, tourism, social infrastructure and land use);
- traffic (road, rail, sea, and air);
- cultural heritage; and
- landscape and visual appearance.

684 Surface water monitoring has been undertaken on the Dounreay licensed site and Mill Lade catchment, with reports issued on the water balance [227; 228], water chemistry [387] and drainage [388]. The water balance studies for the Mill Lade catchment and the site drainage system have been updated [389; 390]. These studies have all informed interpretation of the D3100 site characterisation and monitoring data [50].

685 A routine groundwater monitoring programme across the licensed site is also undertaken by DSRL in compliance with the site Permit. The sampled boreholes

include several in the vicinity of D3100 (see Figure 6.1 in [226]). As well as providing the basis for the hydrogeological conceptual model for the Dounreay site [226], information from these boreholes informed the development of the hydrogeological conceptual model for the D3100 study area prior to the drilling of the site investigation and monitoring boreholes for D3100.

10.2 D3100 Project Monitoring

686 This section is split into a description of the early planning of the monitoring for D3100, where the scope covered all drivers on the project collectively, and a description of the current situation with regard to ESC-related monitoring activities only.

10.2.1 Project-level Monitoring Plan

687 A high-level Monitoring Plan for D3100 was developed in 2007 and updated in 2010 [391]. The scope of the Monitoring Plan was broader than environmental monitoring for the ESC and considered monitoring objectives in terms of four areas:

- **Long-term safety case**. Adopting a risk-based approach, as advocated by the GRA, results from the post-closure D3100 PA [276; 278] were used to identify assessment parameters significant to long-term performance and/or building confidence in long-term performance that are suitable for monitoring. It is highlighted that in identifying parameters that underpin the long-term safety case, there is no implication that there has to be a need to monitor them over a long period.
- **Operational safety case**. Again, following a risk-based approach, the Preliminary Safety Report [30] and accompanying hazard and operability (HAZOP) study for D3100 were used to identify operational safety issues and associated monitoring parameters and requirements.
- **Environmental impact assessment**. The Environmental Impact Assessment of the facilities conducted for the planning application [16] included a number of monitoring commitments to mitigate the potential environmental impacts of the planned facilities.
- **Other objectives**. Monitoring administrative control of the facilities, waste management developments, the regulatory framework, and public reassurance are additional objectives defining monitoring needs.

688 For each objective, the Monitoring Plan defined the information requirements in terms of monitoring parameters, with suggested techniques for undertaking the monitoring of the parameters. The monitoring parameters for each objective were then grouped into monitoring programmes, each concerned with a set of related parameters (e.g. the groundwater monitoring programme covers hydrogeological parameters and groundwater chemistry parameters). The duration of each monitoring programme was defined in terms of the stages of development of the facilities, as set out in the GRA [19]:

- pre-construction;

- construction;
- operations (which will run in parallel with phased construction);
- closure (which will proceed in parallel with phased operations); and
- post-closure.

689 Outlines of the procedures and techniques for collecting and assessing monitoring data for each monitoring programme/parameter were provided in Monitoring Plan 2010 [391]. However, it has been necessary to formalise these outlines for individual monitoring programmes in more detail in separate implementation plans. For example, for groundwater and surface water monitoring, the Environmental Monitoring Programme [392] specifies locations, measurement and evaluation details and schedules, and reporting requirements. The Monitoring Plan and implementation plans together address the desired features of a monitoring and surveillance programme for near-surface disposal facilities, as identified by the IAEA [393].

10.2.2 ESC-level Monitoring

690 The description of monitoring for the purposes of this ESC is restricted to those activities defined in the Environmental Monitoring Programme (EMP [392]). Other observational activities undertaken to build confidence in the ESC are planned and managed under the auspices of the ESC Management Plan [384] referenced earlier in connection with the register of uncertainties [363] (see paragraph 677). The EMP covers all of the environmental monitoring requirements for D3100. It currently contains details of monitoring of:

- groundwater and surface water – this includes water quality monitoring on a quarterly and annual basis to compare with geochemical and radiological baseline conditions (see paragraph 692), and groundwater level monitoring on a quarterly and bi-annual basis to confirm the impact and extent of dewatering;
- skyshine – this includes monitoring of field dose rate measurements to determine if significant changes occur that are attributable to D3100, and review of results from a single Thermoluminescent (TLD) dosimeter in conjunction with a review of operator doses (as the calculated skyshine impact is below the detection limit for a TLD this monitoring is only planned for a short period to confirm expectations); and
- cliff erosion and climate change – cliff erosion will be monitored and compared to the baseline following vault closure and thereafter every 25 years, and the literature predictions for sea level rise (which is currently offset by the post glacial rebound of the land in the north of Scotland) are reviewed every 5 years, with the next review planned following publication of the Intergovernmental Panel on Climate Change (IPCC)'s AR6 report expected in 2022.

691 The EMP also contains an action to review the options for monitoring Demolition LLW settlement in the medium-term and to develop plans for post-closure monitoring in the longer-term. All of these developments will consider BPM [394].

692 Condition 11.4 of the Permit [14] requires DSRL to agree a baseline for the groundwater monitoring with SEPA. Prior to the start of excavation for D3100, DSRL undertook groundwater monitoring from 2009 to 2011 to establish a baseline for groundwater levels and for both surface water and groundwater chemistry. This baseline is documented in [235].

693 An annual review of all D3100 environmental monitoring activities is prepared by DSRL in accordance with Condition 11.6 of the Permit [14] (e.g. [395; 237; 238]), in line with the different areas of data collection set out within the EMP [392]. The annual review presents the data collected for the period in question and evaluates the monitoring data against defined performance measures (i.e. the monitoring data are compared to the agreed baseline conditions (see above) and the changes predicted by the geochemistry model, where appropriate). The annual report also comments on the quality of the data and identifies improvements to be made in the EMP. In addition to the annual report, DSRL notifies SEPA where values of species are detected above agreed baseline levels within the local hydrology.

694 In addition to the ongoing continual analysis of the monitoring data, as reported in the annual reviews, a compilation of all of the environmental monitoring data collected from 2011 to 2018 was evaluated against the pre-construction baseline in [239]. The monitoring data are considered to be consistent with the conceptual models in this ESC. Some additional minor investigations were suggested to help in the future evaluation of data; in particular, an analysis of the minerals precipitating in the walls of the D3100 excavations and in the excavation sumps was undertaken [246].

695 The monitoring parameters and programmes may be reviewed and altered at any time, although this requires agreement from SEPA before their implementation. The EMP will be updated periodically through event-based review (i.e. where significant change or a new project need is identified). For example, prior to construction of the Phase 2 vaults, it will be necessary to review modelling requirements and resources for estimating inflows (e.g. development of a transient modelling capability). Ideally, this review will involve discussion with the construction team.

696 Each monitoring programme can be terminated when it has been assessed that there is no further need for the monitoring of the parameters in the programme (e.g. at the end of operations), or where sufficient data have been collected to satisfy the relevant stakeholders that the performance measures are being met for each parameter and there is no benefit from continuing the monitoring.

FP.11 Continue to develop and implement the Environmental Monitoring Programme for D3100.

11 INSTITUTIONAL CONTROL

GRA 6.3.7(a)	Show that the controls proposed for the period of active institutional control are sufficient to support the claims made for the period of control and that the arrangements for applying the controls can be relied on to be implemented as planned.
GRA 6.3.7(b)	A claim for active institutional control will need to be supported by detailed forward planning of organisational arrangements and a suitable demonstration of funding arrangements.
GRA 6.3.8	Include provisions for site surveillance with scope for remedial work if needed, a programme of environmental monitoring, control of land use and arrangements for the preservation of records. It will need to be supported by evidence that these provisions can be relied on to remain effective throughout the claimed period of time.
GRA 6.3.54	Where there is a difference between practical measures to reduce the likelihood or consequences of disruption and what can reasonably be claimed in the ESC (because of uncertainties surrounding human intrusion), the operator/developer may be required to adopt practical measures that go beyond what is accepted as a substantiated claim in the ESC.

697 This section addresses the detailed requirements in the GRA related to institutional control of D3100. The GRA [19, §11] defines active institutional control as:

> *"Control of a disposal site for solid radioactive waste by an authority or institution authorised under RSA 93, involving monitoring, surveillance and remedial work as necessary, as well as control of land use."*

698 The GRA requires that assessments of the post-closure safety of a disposal facility do not rely on indefinite control over the site (consistent with *Principle P4: Reliance on Human Action*). However, an initial period of institutional control can be assumed, during which activities leading to exposure to hazards are controlled and managed. It is DSRL's responsibility to determine the period for which control is assumed and to justify the assumptions regarding this period of control. A review of approaches to institutional control was undertaken during Stage 1 of the D3100 project [396].

699 Two types of institutional control can be recognised: *active*, involving maintaining an active presence at the facilities as defined in the GRA; and *passive*, involving signs and information to warn people about the facilities. Different assumptions about the effectiveness of these two types of control must be made because of the different levels of uncertainty associated with them. The key uncertainty with respect to active institutional control is the period over which it is maintained, because during this period it can be assumed to be 100% effective in preventing inadvertent intrusion and inappropriate activity at the site. The key uncertainty regarding passive institutional controls is the extent to which they are assumed to be effective over time in informing people about the facilities.

700 In conjunction with plans for the control of the adjacent Dounreay licensed site, active institutional control for D3100 could be assumed for up to 300 years following closure. One objective for active control might be the desire to eliminate the potential for inadvertent disruption of the facility while the short-lived beta/gamma activity in the waste decays. However, as is illustrated in Figure 7.16(a), the calculated annual

doses to an inadvertent intruder only drop sharply for the first hundred years after closure. Thereafter, the calculated doses relate to long-lived activity and drop only gradually. In any event, the calculated doses from inadvertent human intrusion are always below the GRA lower dose guidance level of 3 mSv/y for the Case B best estimate inventory (Figure 7.16), although a few years of access control is required to reach this point for the Case C and Demolition LLW upper estimate inventory (Figure 7.23). It should be remembered, however, that the Run 5 PA and the results shown in these figures do not include short-lived radionuclides with a half-life of less than five years. This is discussed further below.

701 Until the actual inventory of waste disposed of to the facilities is known, it is difficult to define the exact period over which active institutional control will definitely be required. As indicated above, it may be possible that an institutional control period after closure is not required, from a purely radiological risk-based perspective of ensuring that the regulatory guidance levels are met. However, as demonstrated by the inadvertent human intrusion calculations presented in Section 7, there is a clear safety benefit in maintaining a short period of active institutional control to prevent construction on top of the facilities and any activities that would disrupt the barriers containing the radioactive waste during the period when the majority decays away. In addition, DSRL will maintain active control for reassurance purposes until agreement is reached with SEPA – and in dialogue with other stakeholders – to revoke the Permit and cease active control.

702 DSRL's current contract with the NDA assumes that the final end state for the Dounreay nuclear licensed site is 2333, which includes an institutional control period of roughly 300 years [397, §3]. Such a period is required to ensure ongoing management of the HAW stores on the site and to allow radioactive decay of residual contamination. This has a significant influence on proposals for the control period for D3100, as the additional resource required to maintain control over D3100 would be relatively insignificant in comparison to the resource needed for the adjacent, much larger Dounreay site.

703 Even if a decision was made for a shorter control period for the licensed site, a period of time would still be required to dispose of the HAW elsewhere (noting that no national facility for such material currently exists), and to undertake reassurance monitoring to demonstrate that residual contamination was behaving as expected and that safety requirements are met.

704 Therefore, given the benefit provided by an active institutional control period for D3100 and the negligible additional cost, the NDA has agreed to DSRL's proposal that the reference position should be that there will be a minimum of 50 years of institutional control after closure of D3100 [397, §4; 398]. Such a control period has been assumed in screening the radionuclides in the 2020 inventory estimate for significance before inclusion in the D3100 PA, leading to non-ingrowing radionuclides with half-lives of less than 5 years being screened out (Section 8.3.1).

705 Furthermore, as there will be little additional resource needed to protect D3100 alongside the resources needed for the Dounreay site as a whole, DSRL states [397, §4] as its position that it is likely that the D3100 control period will align with any extended control period implemented for the Dounreay licensed site.

706 The EASR 18 Permit [14, Condition 10.2] requires that:

> *"You must, prior to the cessation of waste disposal, produce a plan for the maintenance of active institutional control following the closure of the authorised place which must be approved in writing by SEPA prior to its implementation and thereafter maintained and implemented."*

707 As part of planning for closure, DSRL will develop an institutional control plan for D3100 that takes account of the regulatory guidance. In support of this, DSRL has prepared a development document that identifies the following issues for consideration in the plan [399]:

- organisational arrangements;
- funding arrangements;
- control of land use;
- monitoring;
- surveillance;
- intervention strategy;
- remedial work;
- record retention;
- withdrawal of the Permit and active institutional control; and
- passive safety measures.

708 In the development of an overall strategy for institutional control, DSRL will consider the potential for passive controls as well as active controls, both during and beyond the period of authorisation. For example, DSRL will ensure that information about D3100, including design details and the inventory, is appropriately disseminated and readily available (e.g. in the National Nuclear Archive at Wick). In particular, local authorities with responsibilities for land-use and planning will be informed and asked to provide this information in responses to any enquiries about development of the area around D3100. DSRL may consult in the future with the local community and other stakeholders on other means of disseminating information and the likely effectiveness of different types of control.

709 DSRL's planning and financial provision for institutional controls will be made in discussion with the NDA on the basis of conservative economic models that will ensure that controls can be implemented and, in the case of active controls, maintained for the period required. The plans for D3100 will be integrated with plans for control of the neighbouring Dounreay licensed site. Decisions about maintaining active controls will be reviewed periodically, depending on the results of any monitoring, and socio-economic developments in the area that could significantly affect land-use.

FP.12 Develop an institutional control plan for D3100.

12 PROGRAMME MANAGEMENT

710 This section addresses the four top-level requirements and the associated guidance in the GRA [19] related to programme management and authorisation of the D3100:

- *Requirement R4: Environmental safety culture and management system.* Section 12.1 describes the DSRL administration of D3100 and the work underlying this ESC.
- *Requirement R1: Process by agreement.* Section 12.2 describes the dialogue between DSRL and SEPA during the development of D3100 and now.
- *Requirement R3: Environmental safety case.* Section 12.3 describes how this ESC is maintained and how it is used in relation to other D3100 regulation.
- *Requirement R2: Dialogue with local communities and others.* Section 12.4 describes the dialogue between DSRL and stakeholders other than the regulators during the development of D3100 and now.

12.1 Environmental Safety Culture and Management System

GRA 6.2.5	**Requirement R4: Environmental safety culture and management system.** The developer/operator of a disposal facility for solid radioactive waste should foster and nurture a positive environmental safety culture at all times and should have a management system, organisational structure and resources sufficient to provide the following functions: (a) planning and control of work; (b) the application of sound science and good engineering practice; (c) provision of information; (d) documentation and record-keeping; © quality management.
GRA 6.2.6	Foster and nurture a positive environmental safety culture, i.e. appropriate individual and collective attitudes and behaviours, and require suppliers to do the same. This culture needs to be reflected in and reinforced by the adopted management system.
GRA 6.2.8(a)	Implement a management system that includes effective leadership, proper arrangements for policy and decision making, a suitable range of competencies, provision of sufficient resources, a commitment to continuous learning and proper arrangements for succession planning and knowledge management.
GRA 6.2.8(b)	The management system should be progressively adapted to provide suitable corporate governance of the organisation over the whole lifecycle of the project, i.e. from the early stages of site investigation onwards until the eventual closure of the disposal facility and any subsequent period of active institutional control.

GRA 6.2.9	The written management arrangements supporting the management system should show how, with an appropriate environmental safety culture, environmental safety is directed and controlled. They should also show how the management system is maintained in a living state through regular review, progressive updating and implementation of the management arrangements.
GRA 6.2.10	The structure of the developer/operator organisation should be appropriate for its needs including, in particular, its responsibilities for environmental safety. The structure should reflect current and foreseeable operations and should show how key responsibilities are allocated. A new organisation should plan for and establish a structure based on a set of organisational structure principles that are linked to the activities it intends to perform. For an established organisation the structure should remain a 'live' issue, so that it continues to match the business needs and maintains clarity about responsibilities.
GRA 6.2.11	The Board, directors and managers of the developer/operator organisation should provide strong leadership to achieve and sustain high standards of environmental safety. In particular, environmental safety messages must be seen to come from the top of the organisation and be embedded throughout its management levels.
GRA 6.2.12	The organisation should be capable and forward-looking so as to secure and maintain the environmental safety of the disposal system for the whole of the lifecycle of the disposal facility. Roles, responsibilities, accountabilities and performance standards for environmental safety at all levels should be clear and not conflict with other business roles, responsibilities, accountabilities and objectives.
GRA 6.2.13	The management system should enable the organisation to develop and maintain the resources and competencies needed to ensure environmental safety. The written management arrangements should show how the organisation achieves and maintains a trained, qualified and experienced workforce that matches the need.
GRA 6.2.14	The organisation may need to use contract resource to complement its in-house capability but the implications of this should be recognised for its ability to remain in control in the short term and longer term. The organisation needs to be a capable operator in its own right and able to oversee and manage the work where it uses contractors. Achieving a suitable balance between employee and contractor numbers should take these aspects into account through a resource plan. The organisation will also need a sufficient capability to ensure that goods and services from its suppliers are of a fit and proper standard to meet the requirements of the relevant RSA 93 authorisation and the environmental safety case.
GRA 6.2.15	Maintain relevant competencies over the lifetime of the facility, including any period of authorisation after closure.

GRA 6.2.16(a)	Policies and decisions at all levels that affect environmental safety should be rational, objective, transparent and prudent. All relevant considerations need to be taken into account whenever a policy is established or decision is made. New policies and decisions need to relate properly to, and build on, policies already established and decisions already made. Rigorous questioning of all factual material presented and assumptions made should be part of policy and decision making.
GRA 6.2.16(b)	Whenever a policy is established or a decision is taken, the reasons for the choice made need to be recorded. The reasons recorded should include the other choices considered and reasons why they were rejected.
GRA 6.2.17	Lessons should be learned from internal and external sources to assure continuous improvement in all aspects that affect environmental safety. A learning organisation should challenge accepted established understanding and practice by reflecting on experience to identify and understand the reasons for differences between actual and intended outcomes. The organisation should seek to learn from external sources, including other industries, both in this country and abroad, analysing and acting on the lessons learned.
GRA 6.2.18	Learning should take place throughout the organisation. Staff at all levels should be encouraged to report any actual or potential problems and to make suggestions to avoid or overcome these problems and to achieve improvements generally.
GRA 6.2.19	Lessons learned should be embedded through a structured system that is rigorously applied. Reviews should be carried out to confirm that the changes have been made and that they have brought about the desired improvements.
GRA 6.2.20	Identify all the key areas in which competency is required and develop a strategy for succession planning and knowledge management in all these areas.
GRA 6.2.21	Where appropriate, the approaches used to fulfil management system functions should be based on principles derived from national and international standards.
GRA 6.2.22	The management system needs to be effective in all work that supports the ESC. This covers most of the things that the developer/operator does and includes, at least: investigating the site; designing and constructing the facility; emplacing the waste; closing the facility; and putting in place any arrangements for active institutional control. It also includes work to document these activities and to provide the ESC.
GRA 6.2.23	The management system needs to be effective in work that supports the environmental safety case specifically during the period of authorisation. This includes demonstrating compliance with the operational limits and conditions that will be included in the authorisation under RSA 93 held by the facility operator. The operator, through the management system, should monitor and assess radioactive discharges from the facility and levels of radioactivity in the environment, to conduct prospective and retrospective dose assessments and report accordingly.

GRA 7.3.10	Demonstrate that the environmental safety case, for both the period of authorisation and afterwards, takes 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; - 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.

711 The safety culture and management system at D3100 are established by the overarching culture and management practised by DSRL for the whole Dounreay site. However, within this framework, DSRL has also separated the waste consignment and waste acceptance functions for D3100. The first part of this section describes the overarching DSRL management system and health, safety and environmental protection policies. The second part of the section then describes the application of the system specifically to D3100 with regard to the functions listed under Requirement R4 of the GRA. This includes the division of responsibilities between waste consignment and waste acceptance as shown in Figure 12.1.

712 While reading the following, it should also be remembered that as part of its safety culture, DSRL is committed to the continual review and update as necessary of its management system.

FP.13	Maintain, review and further develop as necessary the management system for operation of D3100.

12.1.1 Overarching DSRL safety policy and management system

713 As set out in DSRL's Safety, Health, Environment and Quality Policy [400], DSRL's priorities are to:

- Minimise risk to everyone.
- Minimise the environmental impact of its activities in terms of resource consumption, pollution and waste creation.
- Sustainably exceed the expectations of its customers and stakeholders.

714 In order to realise these aims, DSRL's policy is to:

- Foster an industry-best safety, health, environment and quality culture through the right personal attitudes and behaviours in a supportive work environment using effective processes.
- Comply with all the applicable health, safety, environment and employment legislation and international treaties.
- Raise any safety, health, environment or quality concerns with line managers before commencing any work.
- Continually improve safety, health, environment and quality performance, by applying learning from experience and seeking improvements through benchmarking.

- Make effective and efficient use of the NDA's funding.
- Establish and resource improvement plans with challenging and measurable objectives and targets.
- Expect the co-operation and commitment of everyone on, or connected with, the site in delivering improved performance.
- Work positively with all interested parties, including regulators, the NDA and all other stakeholder organisations and individuals; strive to understand their needs and meet their requirements.
- Ensure the organisation's purpose and strategic direction are continually monitored and reviewed against any relevant internal and external issues.

715 This policy is implemented for all activities at Dounreay through the ongoing development of an integrated and documented Health, Safety, Environment and Quality Management System that meets the requirements of ISO 9001, ISO 14001, BS OHSAS 18001, HS (G) 65 and IAEA GSR Part 2. This policy is communicated to all persons on site and is made available to the public. Dounreay was the first nuclear site to be awarded the British Standard BS OHSAS 18001, which emphasises wider cultural issues of safety management, such as leadership and worker participation.

12.1.2 Planning and control of work

GRA 6.2.24	All work that supports the environmental safety case needs to be properly planned and controlled. Any changes need to be made within a well-defined change control procedure, described in the written management arrangements, that assures quality and includes decision-making, doing the work and recording what has been done.
GRA 6.2.25	Planning considerations need to include protection against, and mitigation of the effects of, human error and unplanned events during construction, operation and closure (for example accidental flooding), where the environmental safety case might be affected.

716 Any project at Dounreay must proceed through planning, implementation, and review procedures that involve setting objectives, evaluating options and strategy, identifying funding, project management and contractual arrangements, and obtaining sanction. A Project Management Plan (PMP) was developed at the start of the D3100 project and was updated as necessary as the project proceeded [401]. This plan ensured that the objectives of the DSRL management system were met during the development of the facilities. Following completion of construction and the start of waste emplacement, the PMP has now been superseded by the OMP [116] and the D3100 EASR Compliance Matrix [394].

717 Various safety, health and environmental (SHE) documents have been and will be produced to consider the SHE aspects of the various stages in the lifecycle of D3100. The Pre-Construction Safety Report [30] is an example of the SHE documentation produced during the development phase of D3100. SHE issues during operations are considered in the OMP [116] and documents such as the D3100 Safety and Environmental Limits and Conditions [402].

718 DSRL ensures that staff and contractors are properly trained to work safely and meet all legal and regulatory requirements. DSRL's contractors on the D3100 project are highly experienced personnel. During planning, key project decisions were generally managed through DSRL/contractor workshops following a formalised optimisation/BPM methodology. Decisions have been recorded in the project documentation and those relevant to the safety case are summarised in this ESC with reference to the supporting documentation.

719 For operations, DSRL maintains an in-house team split according to waste handling and waste compliance (Figure 12.1). The team is supported by DSRL staff, who provide assurance that the project complies with Dounreay-wide requirements, and also provide support for communications, procurement and finance, and lifetime planning. In accordance with standard DSRL management procedures for an Authority to Operate (ATO), the in-house team conducts an annual Self-Assessment Report for D3100 (ATO104, e.g. [403]).

720 Succession management ensures that appropriate knowledge is transferred through the project. As necessary, project documentation and outputs undergo review by an internal DSRL technical committee to ensure that appropriate emphasis is being placed on safety issues and that appropriate project decisions are being taken.

721 As noted in paragraph 677, the D3100 project has developed a register of uncertainties and an ESC Management Plan [361; 362; 363; 384]. Uncertainties relevant to the safety case are recorded in this ESC, and the action plan to manage these uncertainties is recorded in the forward programme in Section 14. Project risks were, and continue to be, managed in line with DSRL procedures on risk management.

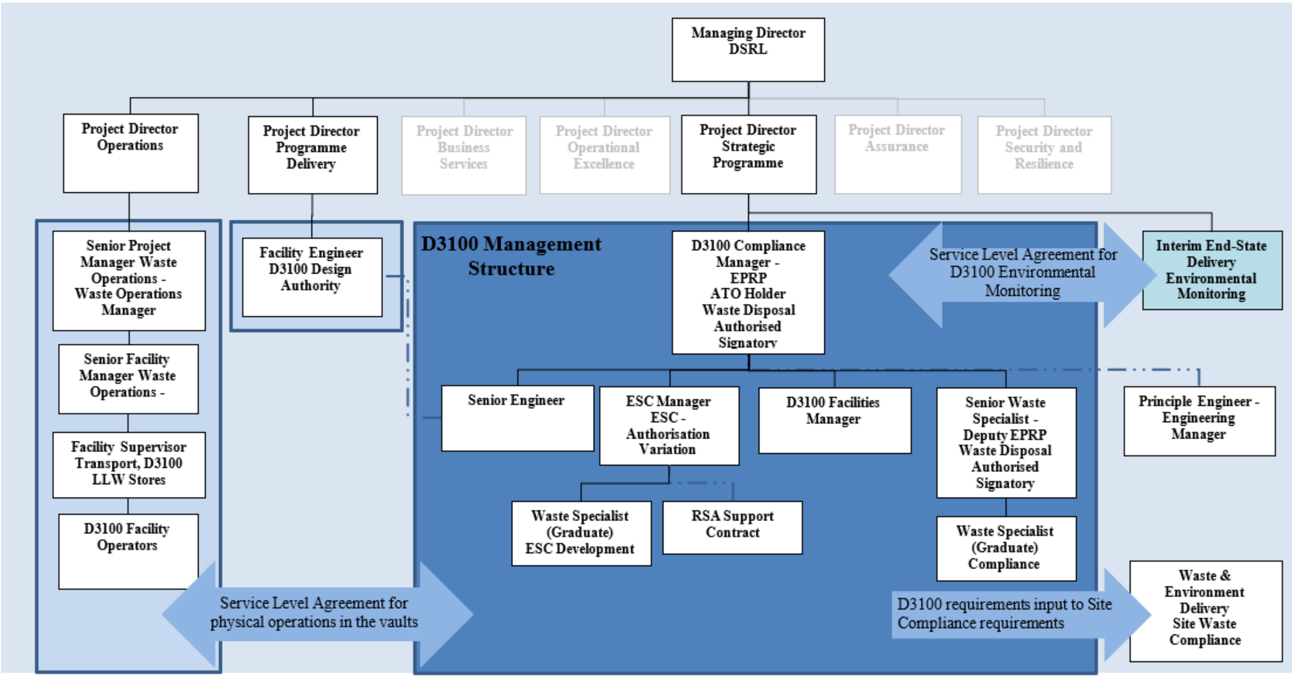

Figure 12.1: DSRL management organogram showing staff with responsibilities for D3100 operations [116, Fig.9.1].

12.1.3 Operational Management Plan and ESC Management Plan

722 An OMP [116] for D3100 has been developed, and is maintained, in compliance with the Permit [14, Condition 9.2]. The OMP takes account of facility design, waste acceptance criteria, and a range of supporting plans, programmes and safety cases. The OMP describes the waste disposal processes for D3100 and the management arrangements necessary to implement disposal. The OMP helps to achieve operational and environmental safety throughout facility operations, in keeping with the ESC assumptions and the EASR 18 Permit.

723 The OMP considers all operations at D3100 and lies immediately below the ESC at Tier 2 in the document hierarchy shown in Figure 2.4. At the level below the OMP, an ESC Management Plan [384] considers the ESC-relevant activities only and provides the links to all of the activities undertaken to address the forward programme in the ESC and the associated register of uncertainties. It comes between the forward programme that is set out in Section 14 of this ESC at Tier 1 and the various activities that implement this programme at Tier 4 (Figure 12.2). It identifies how the outputs of the activities, such as monitoring, waste acceptance, and research and development (R&D), might affect the ESC. It therefore helps to plan work and ensure that, if changes are proposed, staff are aware of ESC aspects that need to be reviewed and the impact assessed.

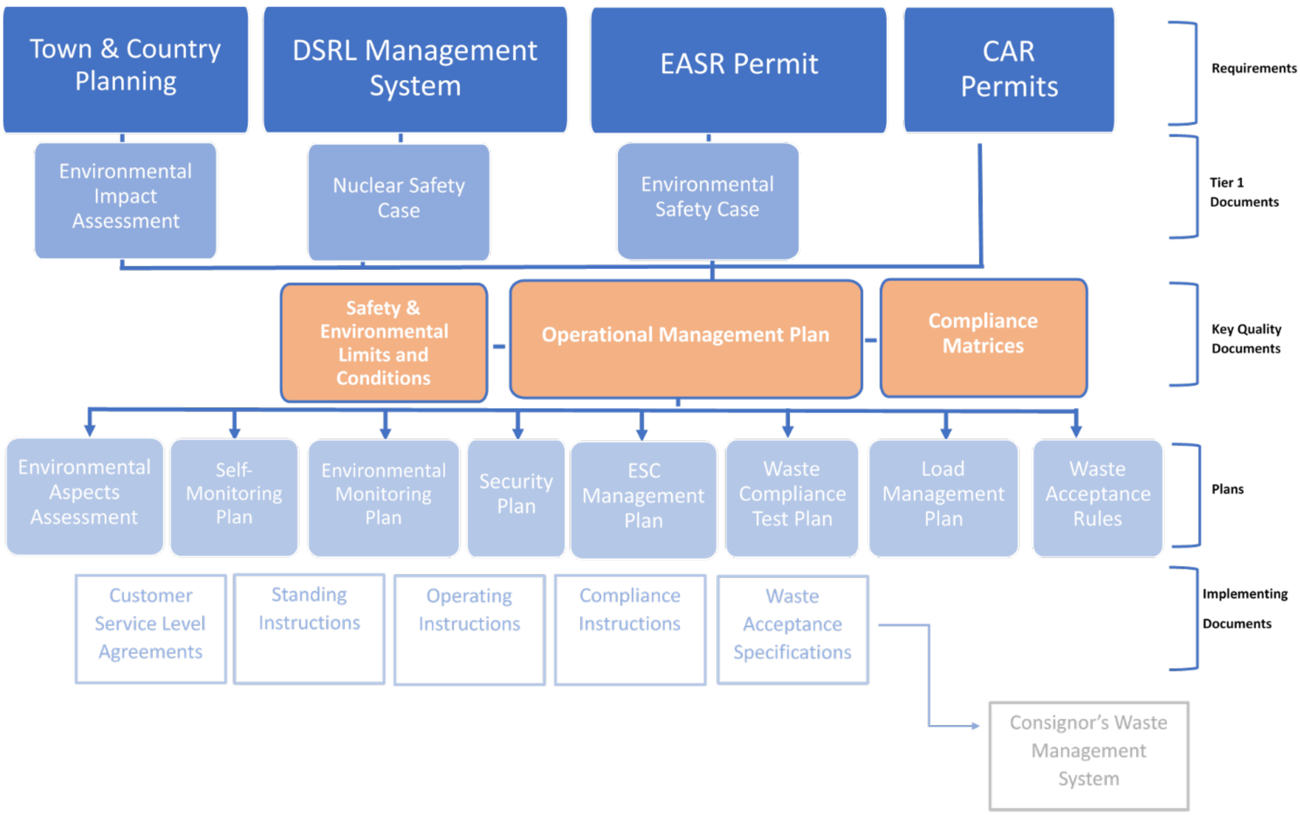

Figure 12.2: D3100 management system summary showing the position of the OMP, WA Rules and the ESC Management Plan in relation to this ESC and the Nuclear Safety Case.

12.1.4 Application of sound science and good engineering

724 Paragraph 657 describes how the D3100 project has ensured it adopts good science. Through DSRL staff and contractors, the D3100 project maintains an awareness of scientific developments in LLW management and PA, both within and outside the UK. Knowledge of such developments feeds into optimisation analyses, including review of past decisions, and planning. The safety strategy for the development of D3100 (see paragraph 3.1) is based on the adoption of robust technology and reliance on passive safety. This is reflected in the design of D3100, which is based on established technology demonstrated in waste management facilities elsewhere.

12.1.5 Provision of information, documentation and record keeping

GRA 6.2.34(a)	The developer/operator will be responsible for all information necessary to support the environmental safety case, and will provide it in a timely way within an agreed documentation structure so that its relevance to the environmental safety case is clear.
GRA 6.2.37(a)	Set up and maintain a comprehensive system for recording information on all aspects of the project affecting the environmental safety case.
GRA 6.2.37(b)	Record: decisions taken and the reasons for them, data and results from the site investigation and characterisation programme; design documents, drawings and engineering details of the facility as constructed; records of waste form and characterisation; records of waste emplacements and their location in the facility; other operational information; details of facility closure; and results of monitoring and assessment at all stages of the project.
GRA 6.2.37(c)	Duplicates of the records will need to be kept at diverse locations and in durable form.
GRA 6.2.37(d)	At the end of the period of authorisation, make arrangement for the records to be included in the public archive.
GRA 7.2.16	Throughout the development and period of authorisation of the facility, preserve the environmental safety case documentation and all relevant records and provide access to these by interested parties.

725 The electronic platforms Achiever, IMAGES and Lotus Notes are key Dounreay systems for holding D3100 information. The DSRL DMS is used for keeping waste records electronically. DSRL uses the NDA Hub web-based system to share D3100 documents of work in progress with contractors and with SEPA. Furthermore, Mainsaver, the DSRL electronic database system used for maintenance of Dounreay plant and equipment, is used for maintaining D3100 plant and equipment. All of these electronic systems are backed-up daily and are therefore considered robust [116].

726 The OMP [116] requires that:

- True, accurate and legible records are retained sufficient to demonstrate whether the limitations and conditions of the EASR 18 Permit [14] are and have been complied with. Any amendments made to a record are to be carried out such that the original remains clear and legible.
- Duplicate records in durable form are to be kept at diverse locations.

- Records made in accordance with the EASR 18 Permit [14] requested by SEPA are to be provided without delay and in the required format.

727 The OMP [116] describes how records related to D3100 are managed and sets this out by information type:

- **ESC Documentation.** The ESC and its supporting underpinning documents are controlled and stored in Achiever. Achiever is a formal DSRL database used for tracking draft reports, through their review/approval process, culminating in publication of final documents in a controlled process.
- **Site Characterisation Documentation.** Site characterisation reports are kept in Achiever. The IMAGES database is a modular system that includes an Invasive Module for keeping information on boreholes, trial pits and trenches, a Monitoring Module for recording borehole monitoring data, and a Documents Module for holding supporting reports. Information in these modules is cross-linked. The IMAGES database will be used throughout the D3100 permitted period. Borehole details, such as locations, logs, and associated chemical analyses, are kept in the IMAGES Invasive Module. Cross-links are in place with other IMAGES modules for retrieval of additional information associated with each borehole. D3100 geological information contained in geological maps and logs is transcribed into DSRL's geological model, described within the Site Characteristics Summary [50].
- **Design and Build Documentation.** Scheme design documents for D3100 and detailed design documents for the Phase 1 vaults were developed as part of the design and build contract. Electronic versions of the documents are maintained on the D3100 Construction Achiever database and drawings within the DSRL drawing registry. Hard copies are maintained as part of the Lifetime Quality Records and Health and Safety File.
- **Wasteform and Characterisation Records.** Paper records associated with a waste package generated at the time of waste consignment are kept in archive stores and can be retrieved as required. For easier accessibility and data retrieval, DSRL uses the DMS for consignment of waste, maintaining and managing waste records electronically.
- **Compliance with the Waste Acceptance.** An electronic record of each waste package consigned to and accepted for disposal in D3100 is kept in the DMS. This electronic record provides the evidence that the consigned waste package meets the WA Rules.
- **Waste Emplacement Locations.** The DMS is used to track and record the disposition of all waste emplacements within the vaults.
- **Quality Management.** The compliance management matrix, which is used to track compliance with all of the Permit conditions, limitations and requirements [394], is published on the Achiever document management system. Records of D3100 QA audits are kept in the DSRL QA database.

728 The management of documents related to the ESC was arranged in the structure shown in Figure 2.4 at the beginning of the development of D3100, as explained in

[404]. The structure was designed as a pyramid to facilitate access in a top-down manner to documents with progressively more detail, and takes account of good practice and international guidance (e.g. [405]). As a web-based system, SEPA can access relevant documents in the NDA Hub system remotely. Further, DSRL has been providing, and will continue to provide, SEPA with additional project documentation as requested.

729 As discussed in Section 11, the Institutional Control Plan to be developed and agreed with SEPA, will set out the approach to management of records beyond the operational phase. This will include details on the format of records for long-term storage, to be aligned with NDA public archive requirements, as well as proposed archive locations and record types. For example, this will include provision of top-level information on D3100 (location, nature, function, content, etc.) to local authorities, the British Geological Survey, the Ordnance Survey, the National Nuclear Archive, and other relevant agencies. Any proposed future redevelopment project in the area should find this D3100 information through a routine contaminated land assessment required under current planning law.

12.1.6 Quality management

GRA 6.2.38	The quality management arrangements should be regularly audited internally and from time to time by an external auditor registered by the International Register of Certificated Auditors.
GRA 6.2.39(a)	Ensure that quality management arrangements are in place to ensure that all information can be traced back to its source.

730 DSRL's quality management system and the quality management systems of its contractors are compliant with the ISO 9001 quality standard. Compliance is verified internally, and externally by accredited certification bodies. Towards the end of Stage 2, DSRL conducted an internal audit of the D3100 project as a check of the project's compliance with Requirement R4 of the GRA and of the general effectiveness of related arrangements [406]. The internal audit covered 76 requirements extracted from the GRA [19, ¶6.2.5 to 6.2.40]. The project was judged to be fully compliant with the vast majority of the requirements. There were three aspects where the potential for minor improvement was identified, and these were addressed.

731 DSRL's Waste and Environmental Delivery (WED) Unit reviews waste against the Dounreay site LLW CfA [112] prior to consignment to the D3100 Compliance Team. The D3100 Compliance Team checks the quality of information supplied and the QA programme of the Dounreay site, as the waste consignor, so as to provide an adequate level of assurance of the acceptable characteristics of the waste. The WCTP [128] details the methodologies used by D3100 to ensure the appropriateness of the consignor's waste management processes, including the implementation of audits targeting the consignor's processes and independent assay of waste items. The objective of the WCTP is to demonstrate that the waste packages disposed of to D3100 meet the requirements of this ESC and the associated WA Rules and, by implication, the relevant Permit conditions. A compliance management matrix is used to ensure compliance with all of the Permit conditions, limitations and requirements [394].

12.2 Interaction with SEPA

GRA 5.2.3	**Requirement R1: Process by agreement.** The developer should follow a process by agreement for developing a disposal facility for solid radioactive waste.
GRA 5.2.4	Enter into an agreement with the regulator to provide advice and assistance after a decision has been made to start a process to select a site for a disposal facility for solid radioactive waste or, before planning a site investigation programme for a disposal facility at a specific location.
GRA 5.3.1	Apply for authorisation under RSA 93 before any disposal of radioactive waste. An application for an authorisation might be submitted before construction if there is sufficient confidence that an environmental safety case can be made.
GRA 5.4.3	Agree with the regulator what submissions should be made and when they should be delivered; these will generally be at points in the programme where decisions to invest substantial amounts of time and resources are required.
GRA 7.2.12	Provide/update the environmental safety case at each step during the development of a disposal facility and at suitable intervals during the period of authorisation to inform and support regulatory decisions in a timely manner.
GRA 6.2.39(b)	On request, allow access to the original data and information on how they were gathered, so that the regulator can examine the provenance and interpretation of the data.
GRA 7.3.22(b)	In cases where there are likely to be extensive modelling studies, discuss the modelling objectives at an early stage with the relevant environment agency.

732 Dialogue with SEPA early in a programme is encouraged in the GRA [19, Requirement R1]. Under Stage 1 of the D3100 project, UKAEA kept SEPA informed of its developing LLW management strategy and of the progress and outcome of the Stage 1 BPEO study. SEPA was asked to comment on the Stage 1 BPEO report.

733 On 19 October 2005, at the start of Stage 2 of the D3100 project, UKAEA held a meeting with SEPA at which the plans for the new disposal facilities and the proposed early submission of the ESC were discussed. Further “technical exchange” meetings have since been held regularly to discuss, inter alia, the content of the ESC (including the underpinning assessments) and the SEPA review process. SEPA committed to review the ESC during 2007/08 (Figure 2.1) to help support its response to the planning application and its decision on authorisation. The SEPA response to Highland Council was provided in July 2008 [407].

734 The project schedule and deliverables to-date shown in Figure 2.1, including issues of the ESC aligned with key project phases, was (and continues to be) discussed with SEPA. Regular technical exchange meetings are held between DSRL and SEPA, and aspects of this ESC were developed in light of discussions at these meetings. SEPA has also provided input on the planning of site characterisation activities. Further meetings with SEPA to discuss technical issues are envisaged as needed throughout operation and closure of the facilities. These meetings might be used to

discuss future modelling, site characterisation, waste acceptance, and monitoring objectives where appropriate.

FP.14 Continue dialogue with SEPA regarding operation of D3100, the EASR 18 Permit, and the ESC.

735 SEPA can access relevant documents in the DSRL D3100 domain of the NDA Hub document management system via the internet. DSRL has been providing, and will continue to provide, SEPA with project documentation as requested. Further, if required, SEPA can visit DSRL offices to view project records.

12.3 Role of the ESC

12.3.1 Current ESC

GRA 6.2.1	**Requirement R3: Environmental safety case.** An application under RSA 93 relating to a proposed disposal of solid radioactive waste should be supported by an environmental safety case.
GRA 6.2.2, GRA 7.1.1 and GRA 7.2.1(c)	The ESC should demonstrate that the health of members of the public and the integrity of the environment are adequately protected. It will be provided by the developer/operator of the disposal facility and should be designed to demonstrate consistency with the principles set out in Chapter 4 of this guidance and that the management, radiological and technical requirements set out in Chapter 6 are met.
GRA 6.2.3, GRA 6.1.2 and GRA 6.2.7	Meet each management, radiological and technological requirement in the guidance in a manner proportionate to the level of hazard the waste the eventual inventory of waste in the facility will present.
GRA 7.1.2	Provide an environmental safety case that responds to the guidance set out in a manner proportionate to the radiological hazard presented by the waste.
GRA 7.2.2	The environmental safety case should include an environmental safety strategy supported by detailed arguments to demonstrate environmental safety. The environmental safety strategy should present a top level description of the fundamental approach taken to demonstrate the environmental safety of the disposal system. It should include a clear outline of the key environmental safety arguments and say how the major lines of reasoning and underpinning evidence support these arguments.
GRA 7.2.3	The ESC should demonstrate, using a structure based on clear linkages, how the environmental safety strategy is supported by the detailed arguments and how the arguments are supported by evidence, analysis and assessment. Internal consistency within the environmental safety case needs to be established and maintained.

GRA 7.2.10(a)	The environmental safety case should describe and substantiate the level of protection provided by the disposal system both during the period of authorisation and in the long term. It should be sufficiently comprehensive and robust to provide adequate confidence in the environmental safety of the disposal system bearing in mind the radiological hazard presented by the waste.
GRA 7.2.10(b)	Be alert to possible future changes to standards and to basic data, and make the environmental safety case as robust as reasonably practicable in this respect.
GRA 6.2.34(b)	Technical information will need to be submitted in an agreed form that allows the regulator to understand fully the arguments put forward in the environmental safety case and to carry out its own environmental safety assessments to support its judgements.
GRA 7.2.14	Consider how the safety case documentation will be structured and updated to promote traceability between steps and transparency. Maintain a detailed audit trail for changes to the environmental safety case and documentation.
GRA 7.2.17(a)	The environmental safety case should be used to help specify a forward programme of improvement work, both to the environmental safety case itself and more broadly.
GRA 5.4.4	Provide a forward work programme for review by the regulator. This should identify the proposed work during the next development phase including discussion of how any regulatory issues are to be addressed.
GRA 5.4.6	The level of detail in the environmental safety case should reflect, for example, the stage of development of the facility, what is known and understood about the selected site, the proposed radioactive waste inventory for disposal and what decision has to be made at the time.

736 As explained in Section 2, the structure of this ESC has been developed to set out as clearly as possible that the principles and requirements in the GRA have been met. Section 3 sets out DSRL's safety strategy and Sections 4 to 12 demonstrate where each requirement has been addressed in the D3100 project documentation. The regulatory crosswalk in Appendix B gives the current status of the D3100 project in terms of addressing each requirement – the overall status is considered appropriate given the status of the project. Despite the revision of the GRA in 2009, the structure of this ESC has been maintained in line with previous iterations as far as possible to promote traceability. It is also noted that an update of the 2009 GRA is anticipated in 2021. A more radical restructuring of the ESC to better fit with the revised GRA will only be done, if required, through discussion with SEPA. However, the current structure has shown itself to be robust to changes in the regulatory guidance and standards.

737 To facilitate review, this ESC has been written to be self-contained, that is, the reader (assumed to be regulators) should be able to understand clearly the safety arguments and supporting evidence without having to delve into other reports. However, if further information is needed for detailed review purposes, then specific references to supporting material have been provided throughout.

738 In several places, the GRA refers to the need for effort to be proportionate to the hazard. As discussed in this ESC and summarised in Section 13, D3100 presents a low hazard. A significant amount of engineering has been included in the design to ensure that radioactivity is contained until the hazard has declined to even lower levels. The design is considered to offer a good balance between achieving short-term containment and low doses, and keeping calculated doses and groundwater contamination in the longer term at a low level. The D3100 project spent several million pounds developing the LLW management strategy, and the consequent design and safety case. DSRL believes that the information base is sufficient to support the operation and closure of D3100.

12.3.2 Future issues of the ESC

GRA 5.5.4	Agree the timing and scope of authorisation reviews with the regulator. To support an authorisation review, submit an updated ESC that includes, for example: − knowledge gained during construction and operation of the facility; − new understanding gained from on-going site characterisation work; − results of continuing research and development studies; − experience from similar facilities in other countries; − technological advances in the characterisation, conditioning and packaging of radioactive waste.
GRA 5.5.6	When waste emplacement ends, submit a post-operational environmental safety case to show that the facility can be closed in a way that allows the principles and requirements of the guidance to be met.
GRA 5.5.7	To support a request for revocation of the authorisation, submit a final environmental safety case to demonstrate that the facility meets the principles and requirements of the guidance. This might be submitted some time after closure of the facility if there is a period of active institutional control.
GRA 7.2.13	Updates to the environmental safety case should reflect growing knowledge about the site and should increasingly reflect the disposal facility as built and wastes as disposed of rather than as anticipated. Updates should also take into account, for example, feedback from regulators and feedback from other relevant facilities, both nationally and internationally, together with developments in environmental safety assessment techniques, in radiological protection and in technical understanding more generally. The eventual aim will be to show that the disposal system as finally realised in practice will provide proper protection to people and the environment.
GRA 7.3.20	The environmental safety case will need to be updated as uncertainties related to the design, construction, operation and closure of a disposal facility are resolved as the programme develops.

739 The forward programme presented in this ESC in Section 14 will be kept under review by DSRL. The ESC Management Plan [384] sets out how the forward programme interfaces with the OMP, waste acceptance, environmental monitoring, and work to address the register of uncertainties.

740 Issues of the ESC will be developed in keeping with the requirements of the EASR 18 Permit [14]. The ESC will be reviewed at three-year intervals in accordance with the

information requirements of Condition 6.3 of the Permit [14]. The review will take account of any further information that has become available in the three-year cycle from activities such as development of future vaults, decommissioning, monitoring, and developments in other radioactive waste disposal programmes. Updates to the ESC will build on these reviews and on discussions with SEPA.

12.3.3 Relationship with non-EASR 18 legislation

GRA 5.5.8	The developer of a near-surface disposal facility might require a Nuclear Site Licence under NIA 65 from HSE. The decision on whether a Nuclear Site Licence is required will be made by HSE.
GRA 7.1.3	If the disposal facility is on a nuclear licensed site, provide a nuclear safety case for the facility that meets the requirements of HSE. The nuclear safety case will have different objectives from the environmental safety case. The arguments presented in the two separate safety cases will need to be compatible.

741 D3100 does not require a nuclear site licence from ONR (in place of the Health and Safety Executive [HSE] in the GRA requirements). However, DSRL has developed most of the documentation that such a licence would require on the basis that it represents good practice for ensuring that health and safety requirements (e.g. those under the Ionising Radiations Regulations 2017) are met. DSRL will ensure that the documentation produced for SEPA and documentation produced for health and safety requirements are consistent.

742 The GRA requirements highlighted in the box at the beginning of this section are concerned mainly with the safety case for a nuclear site licence. However, as mentioned in Section 2, the development of D3100 has had to comply with, and obtain permissions under, other environmental protection legislation. For example, drainage arrangements have required a licence under the Water Environment (Controlled Activities) Regulations (CAR), and storage of excavated material required a Part A Pollution Prevention & Control (PPC) permit. In addition, planning permission received under the Town and Country Planning (Environmental Impact Assessment) (Scotland) Regulations imposes constraints on the design and location of the facilities, including limiting the consigned waste to LLW and setting the volumetric limit. As for the health and safety documents, DSRL will continue to ensure that the documentation produced for any requirements outside the scope of this ESC is consistent with this ESC.

12.4 Interaction with Other Stakeholders

GRA 5.7.1	**Requirement R2: Dialogue with local communities and others.** The developer should engage in dialogue with the planning authority, local community, other interested parties and the general public on its developing environmental safety case.
GRA 5.7.2	The developer is expected to engage widely in discussion of its ESC. Flexible approaches for engaging in discussions are required that adapt to meet a community's needs and expectations.

GRA 5.7.3	Consider, in discussion with the relevant local authorities, how to define “local community” for any specific proposal, taking into account the nature, size and location of the proposed facility.
GRA 5.7.5	Work with the regulator to make sure that discussions with the planning authority and local community are open, inclusive and constructive. Technical, social or economic issues that might affect development of a disposal facility should be discussed openly with explanations of what the operator or regulator is doing to deal with these issues. Local communities and others should also be able to challenge the views of the developer and/or regulator on technical and other issues.
GRA 7.2.15	Present the environmental safety case in a way that people will understand. Different styles and levels of documentation are likely to be needed to present the environmental safety case to different audiences, but these should be consistent in referring to the same fundamental arguments.
GRA 7.3.11	Provide explanations for interested parties of the significance of uncertainties important to the environmental safety case, by presenting these explanations in a way that people will understand.

743 UKAEA engaged with a large number of stakeholders during the Stage 1 BPEO study [7], and as part of consultation on the Stage 2 planning application. As part of the consultation process for the EIA [16], the following stakeholders were consulted:

- Statutory consultees were asked for their opinions by letter as part of the scoping exercise: SEPA, Scottish Natural Heritage, Scottish Ministers, Caithness West Community Council (CWCC), Transport, Environmental and Community services, Highland Council archaeologist, and Historic Scotland.
- The Environmental Statement was provided to local Community Councils, Caithness Business Club, Chamber of Commerce, Caithness Field Club, Caithness West Community Council (CWCC), Members of Parliament (MPs), Members of the Scottish Parliament (MSPs), HSE, the Vulcan facility, Scottish Water, Orkney Council, Shetland Council, and SEPA (local office).
- Press releases and letters were issued to local newspapers.

744 Meetings regarding D3100 during development of the facilities were also held with the following stakeholders:

- Near neighbours and local community – several meetings were held, for example those reported in [408] and [409].
- Individual meetings with near neighbours.
- Dounreay Stakeholder Group.
- Caithness West Community Council.
- MPs and MSPs – individually at site and through a presentation at Scottish Parliament.
- Scottish Natural Heritage - three meetings.
- Numerous meetings with Highland Council representatives.
- Staff at the local SEPA office in Thurso.

- Numerous meetings with HSE and SEPA radioactive substances regulators.

745 To help cohesion between DSRL and regulator/public consultation activities, SEPA attended some of the meetings between DSRL and stakeholders. The stakeholder dialogue process during the development of D3100 is summarised in the Stakeholder Engagement Plan [410], which has since been updated to account for the proposed changes to the interstitial grouting process and the Permit variation application [411]. Now that D3100 is operational, stakeholder dialogue is conducted routinely through the Dounreay Stakeholder Group.

746 As part of the dialogue process, a non-technical summary of the project aimed at a non-technical audience was prepared for the 2008 planning application, and this summary has been updated as necessary [96]. A non-technical summary of this ESC has also been prepared and, similarly, updated as necessary [95].

FP.15 Continue dialogue with stakeholders.

13 SUMMARY OF THE SAFETY CASE

747 On the basis of the material presented in this ESC, D3100 complies with the fundamental protection objective and all of the associated principles for the protection of the public set out by the environmental regulators [19].

748 **Fundamental protection objective.** Following an evaluation of environmental, safety, social, technical, and financial issues, DSRL is dealing with its LLW at source using specialised disposal facilities at Dounreay. D3100 meets the fundamental protection objective for disposals of solid radioactive waste set out by the environmental regulators. The LLW is generally inert and its radioactivity content lies at the lower activity end of the radioactive waste spectrum. The disposal facilities are designed using well-established technology, are consistent with national and international guidance, and are similar to established LLW disposal facilities elsewhere in the UK and Europe. Compared to conventional disposal facilities for non-radioactive waste, D3100 uses a high level of engineering to ensure that the majority of the radioactivity is contained until it decays. Containment levels are expected to be close to 100% for hundreds of years and potentially even longer as the engineering slowly degrades. The quantities of radioactivity that might be released from the facilities are lower than quantities of radioactivity that are naturally present in the environment. Consequently, impacts on people and the environment from the facilities will be significantly less than impacts from background natural radiation that people are exposed to in their everyday lives.

749 **Principle 1: Level of protection against radiological hazards at the time of disposal and in the future.** D3100 has been designed such that there will be no meaningful releases of radioactivity to the environment during operations. Post-closure radiological performance has been assessed by safety assessments that conform to international good practice. Levels of assessed post-closure dose and risk from D3100 are below the regulatory safety criteria: the dose constraint during the authorisation period; and the risk guidance level and human intrusion dose guidance level during the post-authorisation period. The risk guidance level is equivalent to a dose of around 0.02 mSv/y, which is an order of magnitude below the level of impact from sources of artificial radioactivity that is acceptable (allowed by regulation) today, and two orders of magnitude below the average UK dose from naturally occurring sources of radiation. Calculated concentrations and fluxes of radioactivity in the environment resulting from D3100 are significantly below naturally occurring concentrations and fluxes.

750 **Principle 2: Optimisation (as low as reasonably achievable).** Each decision in the development of D3100 has considered optimisation of the radiological impacts, taking into account issues such as economic and societal factors, to ensure that these impacts are As Low as Reasonably Achievable (ALARA). The long-term waste management strategy, and the location and design of the facilities, represent the optimised solution decided to date. The engineering assures nearly complete containment of radionuclides in the facilities in the next few hundred years, while the hazard drops to levels comparable to background radiation. The location of the vaults ensures that the short-term impacts to near-neighbours from construction and operation are as low as reasonably achievable given the need to protect D3100 from coastal erosion and possible future sea-level rise. The enhanced geosphere layer

further reduces already low calculated doses via the terrestrial exposure pathway. Measures to reduce the likelihood of inadvertent human intrusion, such as placing the vaults underground and installing a thick cap, have been included. Optimisation studies will continue to be undertaken as further decisions are taken during any future design and construction activities, and during operation, closure and post-closure management of the facilities. The use of a SoF approach during waste acceptance enables flexibility for optimisation of future disposals and making best use of the facility space.

751 **Principle 3: Level of protection against non-radiological hazards at the time of disposal and in the future.** Only a few non-radiological hazardous (NoRaH) contaminants are anticipated to be present in D3100 in any significant quantity, and will be in inert forms or will be rendered inert by the waste conditioning. The high-quality engineering of the vaults and the waste conditioning represent the use of good practice for long-term containment of the NoRaH contaminants in the LLW, which, in combination, exceed the engineering required for hazardous waste disposal facilities. A suitable level of long-term protection of the environment against NoRaH is provided by both the LLW and Demolition LLW vaults.

752 **Principle 4: Reliance on human action.** Active institutional control is foreseen after closure of D3100 in order to ensure no inadvertent human intrusion of the facilities. Following the withdrawal of active control, the wastes are likely to remain isolated from disturbance by foreseeable natural disruptive events for at least 10,000 years. Although it is not possible to guarantee no releases of radioactivity over the timescales of the decay of the long-lived radionuclides, the engineering of D3100 is such that over 98% of the disposed of radioactivity will decay before it can be released under the undisturbed evolution of the system. The good performance of D3100 in this regard does not depend on actions by future generations to maintain the integrity of the disposal system.

753 **Principle 5: Openness and inclusivity.** This principle applies to SEPA, but with the expectation that a site developer would operate in an open and inclusive way. DSRL has adopted an open process and engaged with a wide range of stakeholders throughout the development of the D3100 project and will continue to do so.

754 The waste to be emplaced in D3100 is of low activity, containing less than 0.01% of the radioactivity that is present in radioactive waste on the Dounreay site, but comprising about 90% of the radioactive waste by volume that is expected to be created during decommissioning and restoration of the site. The waste to be disposed of meets the internationally accepted definition of short-lived radioactive waste suitable for near-surface disposal.

755 D3100 will fulfil the safety strategy and achieve the top-level safety functions outlined in Section 3 thus:

- **Isolation.** In general, the LLW will be encapsulated in cementitious material. During operations, the waste packaging and conditioning shield workers from radiation and provide a passive and stable wasteform for handling and emplacement. After closure, the below-surface setting and cap design isolate the wastes from human activities. Active institutional control will ensure that the wastes remain isolated from inadvertent human intrusion while radioactivity levels drop significantly by decay. The stable geological environment ensures that the waste will remain undisturbed other than by groundwater infiltration at least until activity in the wastes has dropped to almost background levels.

- **Containment.** Keeping the facilities dry during operations, along with the waste packaging and conditioning, ensures that there will be no releases of radioactive material (radionuclides) during the operational period. The only method of exposure of the public will be through skyshine (interaction of electromagnetic radiation from packages with the air). The majority of the radioactivity to be disposed of in D3100 derives from short-lived radionuclides (i.e. half-lives shorter than approximately 30 years). In general, the facility engineering will contain this activity in the facilities until decay. In a few hundred years after closure, roughly 90% of the total radioactivity disposed of in the facilities will have decayed, and the hazard from the waste will be significantly reduced. Also, the geosphere will provide some additional containment.
- **Delay and attenuation.** The engineering designed into D3100, and the surrounding geosphere, will limit the migration of radionuclides. The design of the facilities is based on the internationally advocated concept of using multiple engineered barriers to provide strength in depth, giving reassurance that even if one barrier exhibits poor performance, the other barriers will ensure that the required overall performance is achieved. The engineered barriers include the concrete box structure of the facilities and the engineered cap, which inhibit migration of water into and out of the facilities. The grout in the LLW vaults and packages acts both to reduce water movement and as a chemical inhibitor to radionuclide migration. In the grouted, alkaline environment, waste containers will corrode slowly thereby acting as an additional barrier to water ingress. Once releases to groundwater occur from the facilities, the low-permeability and potentially reducing geosphere environment will further attenuate the migration of the radionuclides. In addition, the enhanced geosphere will help minimise the flow of contaminated groundwater up into the soil zone.

756 The calculated peak annual releases of alpha and beta/gamma activity from D3100 into the environment and, more specifically, into the sea, are less than current permitted annual liquid discharges from the Dounreay licensed site into the sea (several orders of magnitude less for beta/gamma activity). Even if the total cumulative releases of alpha and beta/gamma activity from the facilities over 100,000 years are considered, the total activity release is only similar to historical Dounreay discharges permitted under the nuclear licensed site Permit for one year. The maximum annual flow or release of radioactivity from the facilities will also only be a fraction of the flow of naturally occurring radioactivity that is currently migrating through the soils and rock. Concentrations of radioactivity in the environment (in rocks, soils, air, water, and vegetation) related to releases from D3100 will be below concentrations of naturally occurring radioactivity. Therefore, releases from D3100 will have negligible effect on the environment.

757 This ESC has been developed in accordance with current legislation, government policy, regulations, and international and national guidance. Information has been

gathered and assessed concerning the characteristics of the site, the facilities, and the waste. There are some areas for further development appropriate to the current status of the ESC, and a forward programme is presented for work in these areas and to build further confidence in the safety case.

758 Appropriate quality systems, monitoring plans, and systems for records maintenance are in place, and will be maintained throughout facility operation. D3100 has a Permit from SEPA under EASR 18 that imposes conditions and Authorised WAC for the radioactive waste disposals. The Permit references ESC 2010. The revision table at the beginning of this document summarises the main changes between ESC 2010 and this iteration of the ESC. Table 13.1 summarises the main changes in this iteration of the ESC with regard to the information specifically referenced in the current Permit for D3100.

759 Development of D3100 is ongoing through an iterative programme of design and construction, operation, safety assessment and review. Via the NDA, there is UK Government commitment to continued funding for the project.

Table 13.1: Main changes from ESC 2010 to this ESC affecting the information referenced in the EASR 18 Permit.

ESC Section	Summary of Change
4.3.2	Schedule 2 of the Permit provides maximum radionuclide inventories that are based on the predicted waste inventory for 2009 in ESC 2010. The inventory predictions have been updated for 2020. Further, DSRL is proposing to use a SoF approach to managing waste acceptance – such an approach uses control levels based on individual safety assessment calculations rather than an inventory prediction – this is discussed below.
4.4 (WA Rules 2.5 to 2.9)	Minor changes have been proposed throughout the WA Rules to better fit with operational experience to-date and compliance with the Permit. In particular, Rule 2.6 in ESC 2010 has been expanded into WA Rules 2.5 to 2.9 regarding management of voidage in waste packages. This follows a series of BPM studies undertaken as part of the ongoing optimisation of disposals at D3100.
7.10 (WA Rules 3 and 4)	The Permit provides Authorised WAC 3.1d, 3.1e and Condition 4 in particular for non-radiological hazards (NoRaH). An updated analysis of NoRaH in the D3100 wastes and proposed revisions in the form of WA Rules 3 and 4 for control of NoRaH are provided.
7.11 (WA Rule 6)	An updated criticality safety assessment and proposed limits for control of fissile material in WA Rule 6 are proposed to replace Authorised WAC 3.1g to 3.1k.
8.4 7.4.3 7.5.3 7.5.4	A table of proposed control levels for 51 individual radionuclides is provided for use in SoF calculations during waste acceptance at D3100. The process of using the SoF calculations is described. The reasons for adopting the SoF approach and the methodology for calculating the control levels are set out in Section 8. The main changes to the assessment modelling used to calculate the control levels are described in Section 7.

ESC Section	Summary of Change
9.3.8 12.1.3	Consistent with Conditions 6.1 and 9.1 of the Permit, DSRL is developing an ESC Management Plan alongside the Operational Management Plan to help ensure that activities at D3100 are undertaken in compliance with the Permit and the results of these activities are fed back, as appropriate, to future updates of the ESC.

14 FORWARD PROGRAMME

760 The ESC is a living document, supported and maintained throughout the life of the facilities. However, “frozen” versions are produced at key points in the programme. As discussed in paragraph 17, four iterations of the D3100 ESC have been produced previously, supporting the planning application, interactions with SEPA and Permit requirements. Future issues of the ESC will be produced if significant changes are required, as identified by the ongoing reviews and optimisation activities, and when an application is made to SEPA to close the facilities and revoke the EASR 18 Permit.

761 Identification of future work to develop and maintain the D3100 ESC has been highlighted throughout Sections 4 to 12. Future work requirements will, however, also be influenced by dialogue with SEPA and stakeholders. The work needs to be phased with regard to the completion of other activities, such as decommissioning on the Dounreay site, and tied in with the development of future issues of this ESC and operation of D3100. Previous iterations of this ESC have also contained a forward programme, and it is worth noting that several activities have been completed since Issue 1 of ESC 2010. For example: design issues such as drainage and addressing the risk of flooding have been addressed; optimisation studies have led to a change in layout, introduction of the enhanced geosphere barrier; the safety assessment has been updated; and management and operational procedures have been developed.

762 The forward programme activities for the future identified in Sections 4 to 12 are listed in order below. However, note that the order is not intended to reflect any priority or perceived relative importance. In addition, many of the identified forward programme activities are rolling actions, in the sense that they relate to activities and assessments that have already been successfully undertaken and only an awareness of developments that may impact the previous work needs to be maintained. Equally, some activities will always be ongoing, such as engagement with SEPA and other stakeholders, and some will only be triggered, such as update of the WA Rules, when a system change is enacted. Other activities, such as development of a D3100 Materials Management Plan, will be undertaken in the near term, and this is considered in the ESC Management Plan [384].

FP.1 Maintain a Waste Management Plan (WMP) and develop a Materials Management Plan for D3100.

763 D3100 WMP requirements are met through a number of documents for D3100, particularly the Environmental Statement [16, Ch.11], the OMP [116, §4] and supporting PSWP [117], and the D3100 Project Phases Interface Plan [118] and enclosed materials mass balance calculations. It is recognised that as disposal operations and backfilling progress, and in anticipation of future phases of construction, review of the WMP documents, material mass balance calculations and development of a materials management plan is required.

FP.2 Maintain dialogue with the Dounreay site end state team, and review the developing Dounreay site Waste Management Plan, to assess the impact of future changes in the site decommissioning and remediation strategy on the wastes requiring disposal in D3100 and the potential for cumulative impacts on receptors.

764 As noted in paragraph 13, as a result of the proposed amendments to the regulatory regime, the Dounreay site end state is under review. Changes in the plans for the site end state could impact the wastes requiring disposal in D3100, which is acknowledged as a current uncertainty in the inventory estimate for D3100 (e.g. see paragraph 90). The D3100 team will continue to maintain interactions with the end state team for the Dounreay site in order to understand the impact on D3100 of any changes to wastes requiring disposal (and therefore the number of vaults to be constructed), and to also understand if on-site disposals are planned and if there is potential for cumulative impacts to D3100 receptors.

FP.3 As necessary, review and revise the WA Rules for D3100.

765 A document setting out the waste acceptance requirements for D3100 has been prepared [54], and these requirements are currently implemented through the WA Rules 2020 set out in the ESC. However, the requirements may need to be reviewed as the operation of D3100 progresses and/or revised for consistency with the varied EASR 18 Permit if additional WAC are included by SEPA in the Permit variation being sought that require flow-down into the D3100 waste acceptance process.

FP.4 As necessary, review and revise the Operational Management Plan and supporting documents for waste acceptance in the D3100 disposal facilities.

766 Operational practices at D3100 are described in the OMP [116]. The OMP includes a load management plan, a compliance management plan and waste acceptance procedures for receiving and checking waste consignments. The OMP is reviewed as necessary and may need revision as the operation of D3100 progresses (e.g. in response to the current trial of more regular backfilling of the LLW vault).

FP.5 As necessary, develop guidelines for BPM assessment for the acceptance and emplacement of non-containerised waste.

767 Only containerised waste has been disposed of so far in the D3100 LLW vaults. No special provisions are currently proposed for the handling and consignment of non-containerised waste, although preliminary WA Rules for non-containerised waste have been developed [54]. A case-by-case BPM assessment of the merits of non-containerised waste emplacement versus size reduction and packaging is necessary, considering issues such as containment during transport, emplacement and grouting of the items, worker dose assessment both at the originating plant and in the vault, and the practicalities of size reduction. Guidance for these assessments will be developed as needed as the cases arise. The waste acceptance requirements and process for non-containerised waste will be reviewed as experience develops.

FP.6 Future design considerations and optimisation analyses.

768 The design analyses to date, as summarised in Section 5, have evaluated a wide range of options. The iterations of the D3100 project BPM/optimisation reports have been reported in this ESC [144 to 149; 51]. As the development and operation of D3100 progresses, more BPM assessments and design optimisation studies may be conducted and refined. Future vaults will be sized according to refined expectations of waste arisings, and vault locations and designs may be tweaked to accommodate, for example, particular local conditions. Further optimisation assessments will be reported in future issues of the ESC.

FP.7 Evaluate site characterisation opportunities during future phases of vault construction.

769 Opportunities to further develop understanding of the site characteristics, similar to the activities described in Site Characterisation Plan 2011 [198] will be considered in advance of future phases of vault construction.

FP.8 Maintain PA capability and periodically review the need for PA updates.

770 The Run 5 PA in support of this ESC has involved reviews of each of the main components of the D3100 PA in light of developments in design, site understanding, and inventory, selection of a SoF approach to waste management, and in light of dialogue with SEPA and developments in regulatory guidance. The full objectives and scope of the next PA iteration will be specified in more detail nearer the time of an identified need for its development. In the interim, the Run 5 PA model may be refined to support other studies, such as optimisation analyses.

FP.9 Maintain, review and further develop as necessary the SoF approach for waste acceptance and management.

771 The activity control levels proposed in Table 8.2 have been calculated using the Run 5 PA models and reflect the design of D3100 and the PA assumptions made. Should fundamental changes be made in the design and layout of the facilities then new PA calculations to determine revised control levels might be needed. The impact of changing inventory estimates on DSRL's ability to flexibly manage disposals to D3100 within the controls applied by the SoF approach also need to be monitored. Changes to the way the SoF approach and calculations are applied may need to be considered to better meet the demands of the D3100 project.

FP.10 Periodically review and update the D3100 project's Register of Uncertainties.

772 Multiple and complementary lines of reasoning and evidence are required to support the ESC. In this context, confidence in the D3100 project PA benefits from validation exercises. Although PA models as a whole cannot be validated directly owing to the modelling timescales involved, conceptual models on which the PA is based can be validated, and the values of model parameters employed can be validated.

773 Periodic review of the D3100 Register of Uncertainties considers the benefits that possible site characterisation, experimental and analogue studies could have in building confidence in the PA models and parameter values. The register is reviewed and updated in synchrony with updates of the ESC, as described in the ESC Management Plan [384].

FP.11 Continue to develop and implement the Environmental Monitoring Programme for D3100.

774 The EMP identifies the environmental monitoring being undertaken for D3100 [392]. The monitoring programme addresses the requirements of the EASR 18 Permit. Periodic reviews of the EMP will be undertaken during the period of authorisation taking account of the developing status of the facilities (e.g. construction of Phases 2 and 3, closure, post-closure). Any necessary amendments will be made with SEPA approval (which is required by the Permit).

FP.12 Develop an institutional control plan for D3100.

775 Both active and passive institutional control measures will be implemented for D3100. These measures need to be set out in an institutional control plan that will need to be integrated with the plans of other projects on the Dounreay licensed site. Further, the period of proposed control may change in response to changes in other projects or through dialogue with SEPA, and a procedure will be needed for periodic review of the plan. Although no credit is taken in this ESC for passive institutional controls, DSRL will also consider any further passive measures that could be taken to deter inadvertent human intrusion after active control ceases. Given that the institutional control plan will not be implemented until closure, its development is currently a low priority compared to some of the other activities described in this section.

FP.13 Maintain, review and further develop as necessary the management system for operation of D3100.

776 DSRL will continue to maintain and review its management system and associated QA procedures to support future programme activities and ensure compliance with Requirement R4 of the GRA. In tandem with development of plans for institutional control, arrangements for the keeping and preservation of records after closure need to be defined.

FP.14 Continue dialogue with SEPA regarding operation of D3100, the EASR 18 Permit, and the ESC.

777 A key input to the planning of any future work will be dialogue with SEPA over regulatory expectations and approaches to key issues. A series of technical exchange meetings with SEPA has already been held and further meetings are envisaged as needed to discuss technical issues as they arise.

FP.15 Continue dialogue with stakeholders.

778 DSRL has developed a non-technical summary of the D3100 project to support its communications strategy and dialogue with stakeholders. The non-technical project summary will be updated as necessary. DSRL will continue to communicate to stakeholders during D3100 operations through the established programme of meetings with the Dounreay Stakeholder Group.

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APPENDIX A D3100 WASTE ACCEPTANCE RULES 2020

A1 Table A.1 contains the revised 2020 WA Rules [54] and a summary of the justification for each Rule, which have been drafted for consistency with DSRL's Permit variation application. The Rules will be updated following SEPA's decision on the Permit variation application to reflect the actual revised Permit conditions.

Table A.1: Draft WA Rules for disposal of solid LLW in D3100, justification for their inclusion and their relevance to stages of the facilities' lifecycle [54].

WA Rule	**Justification and Relevance to Operations (O), Transport (T) and/or Post-closure Environmental Safety (PC)**	
1. Compliance with the waste acceptance process		
1.1 A waste package will not be accepted for disposal to D3100 unless it has been approved through the Dounreay Waste Management System. 1.2 Waste will only be accepted from the Dounreay Nuclear Licensed Site and the Vulcan Naval Reactor Test Establishment. 1.3 A waste package will not be accepted for disposal to D3100 unless it has been demonstrated by the waste consignor that Best Practical Means (BPM) and the waste hierarchy have been applied to generation, characterisation, management and disposal.	• To ensure that all of the assumptions and assessment results presented in the ESC are upheld. • To ensure that there is no compromise of safety during transport, operations, closure and post-closure phases. • Regulatory requirement to demonstrate BPM and application of the waste hierarchy. • To ensure waste characterisation is sufficient to enable assurance that the assumptions in the ESC and underpinning safety assessments are appropriate and valid.	O, T & PC
2. Physical characteristics of the waste packages		
2.1 **Containerised LLW** shall only be accepted for disposal if the waste is held within a container approved by the D3100 Environmental Permit Responsible Person (EPRP) and D3100 Authority to Operate (ATO) Holder. **Demolition LLW** shall only be accepted for disposal if the waste is held within a container approved by the D3100 EPRP and D3100 ATO Holder. 2.2 It must be demonstrated that all approved containers are in a fit physical state to hold and	• Ensures safe handling, transport and disposal operations. • LLW containers have to be capable of supporting overlying containers within the stack. • Lower floor of grouted waste has to be capable of supporting the intermediate floor slab and overlying waste containers.	O, T & PC

WA Rule		Justification and Relevance to Operations (O), Transport (T) and/or Post-closure Environmental Safety (PC)	
	contain the waste, and to allow safe transport and disposal operations.	• Fully grouted waste mass has to be capable of supporting vault cap for LLW vaults. • LLW containers will also act as an engineered barrier for waste containment after operations, but no credit is taken for this in the ESC. • Labelling ensures package traceability and load management within the vaults and is a Permit requirement.	
2.3	The waste package shall be labelled with a unique identifier, and where practicable, indication of the radioactive content.		
2.4	The weight of a package accepted for disposal must be compatible with the load-bearing capacities of its container (if any), safe handling, transportation and disposal operations and with the load-bearing capacity of the vault floor.	• Ensures safe handling, transportation and disposal operations, including the emplacement of Demolition LLW bags in layers.	T, O & PC
2.5	Packing of waste items inside a container must be demonstrated to be optimised to minimise accessible and inaccessible voidage.	Vault cap designs have not been finalised. Estimates of voidage in the vaults will be needed to inform cap design. In order to ensure that cap design does not need to be overly constrained, these Rules ensure: • Grouted contents of a container do not suffer settlement when subject to mechanical loads. Waste settlement during post-closure could lead to cracking of the grouted matrix and the potential creation of pathways for water ingress. Post-closure settlement could lead to partial collapse of the emplaced containers that could weaken support for the lid, and in turn result in crack formation in the lid and, potentially, unwanted upward water flow. • The lid of a Demolition LLW vault will be designed to cater for post-closure waste settlement, but voidage in	PC
2.6	Voidage in a **LLW** package that is inaccessible to grout must be demonstrated to have been minimised as far as reasonably practical.		
2.7	Voidage inside a **LLW** package that is inaccessible to grout, including ullage, should not exceed 10% of the internal container capacity unless a higher percentage has been agreed in advance through an exception process.		
2.8	Voidage inside a **Demolition LLW** container must be demonstrated to have been minimised as far as reasonably practicable.		
2.9	Inaccessible voidage must be estimated and reported in the waste package evidence pack.		

WA Rule		Justification and Relevance to Operations (O), Transport (T) and/or Post-closure Environmental Safety (PC)	
		Demolition LLW must be minimised to reduce cap design constraints.	
2.10	No free liquid is permitted in a waste package.	• D3100 is only permitted to dispose of solid LLW. • Free liquid is excluded from containerised and non-containerised LLW to prevent early container degradation and early radionuclide release. • Free liquid is excluded from Demolition LLW to prevent early degradation of the bag, early saturation of the vault, safety/handling issues and early radionuclide release.	O, T & PC
2.11	All approved packages of **LLW** shall be infilled with cementitious grout of an approved composition prior to disposal unless it has been agreed through an exception process that in-vault grouting is acceptable for HHISOs that would otherwise breach the transportation weight limit.	• Ensures that cementitious material surrounds LLW, as envisaged in the ESC, to achieve long-term mechanical stability and chemical conditioning.	PC
2.12	The forecast volume of waste streams to be disposed of to D3100 should be estimated by the consignor and annually reviewed with the D3100 EPRP to ensure consistency with the total waste volumes presented in the ESC and specified in the EASR Permit and planning application.	• To ensure compliance with planning approval. The Highland Council granted planning permission for D3100 on the basis of 6 vaults with a total volume of 175,000 m^3 (130,000 m^3 LLW and 45,000 m^3 Demolition LLW). • Allows D3100 Compliance Team to track disposal inventory against predictions to ensure assumptions in the ESC and Performance Assessment (PA) remain valid, and to inform future vault sizing/design.	PC
3.	**Chemical characteristics of the waste packages**		
3.1	Hazardous materials must be excluded from **non-containerised LLW** and **Demolition LLW** packages unless their inclusion has been approved through an exception process.	• Ensure that chemical characteristics of the wastes do not breach conventional waste management regulations or	O, T & PC

WA Rule	Justification and Relevance to Operations (O), Transport (T) and/or Post-closure Environmental Safety (PC)	
3.2 Hazardous materials in **containerised LLW** packages must be prepared and made safe for transport and operations before the waste can be accepted for disposal. 3.3 The hazardous content of raw waste must be declared by the waste consignor. The method of preparing the hazardous content so that it is safe for transport and operations must also be declared, even where the method is grouting of the package in the D2179 grout plant. 3.4 The ion exchange material content of a waste package should not exceed 1% of the weight of the package unless a higher percentage has been agreed in advance through an exception process. 3.5 The ion exchange material type and content in the raw waste must be declared by the waste consignor. The ion exchange material must be prepared and stabilised before the waste can be accepted for disposal. The method of preparing the ion exchange material so that it is stabilised must also be declared and justified.	compromise safe management during transport, operations, disposal and post-closure. • Allows D3100 Compliance Team to track disposal inventory against predictions and ESC assumptions.	
4. Biological characteristics of the waste packages		
4.1 Pathogens and other biologically hazardous materials must be excluded from **non-containerised LLW** and **Demolition LLW** packages unless their inclusion has been approved through an exception process. Pathogens and other biologically hazardous materials in **containerised LLW** packages must be prepared and made safe before the waste can be accepted for disposal. 4.2 The pathogenic or biologically hazardous content of raw waste must be declared by the waste consignor. The method of preparing it so that it is safe must be declared, even where the method is grouting of the package in the D2179 grout plant. 4.3 Waste liable to be readily decomposed by micro-organisms (i.e. putrescible or biodegradable waste) such as food, vegetable or animal remains, aside from paper and similar materials that degrade more slowly, must be demonstrated to have been excluded as far as is practicable, and in any event	• Ensure that biological characteristics of the wastes do not breach conventional waste management regulations or compromise safe management during transport, operations, disposal and post-closure. • Allows D3100 Compliance Team to track disposal inventory against predictions and ESC assumptions.	O, T & PC

WA Rule		Justification and Relevance to Operations (O), Transport (T) and/or Post-closure Environmental Safety (PC)	
	must not exceed 1% by weight of any waste package.		
5. Radiological characteristics of the waste packages			
5.1	For each vault, the sum of the ratios of the amount of each radionuclide disposed of ($A_{Disposed,Rn}$) to the Calculated Activity Concentration Level for each radionuclide ($CACL_{Rn}$) set out in Table 3.2 and Table 3.3 below shall be less than 1. *Rn* represents an individual radionuclide, and there may be up to *n* radionuclides present. $$\sum_{Rn=1}^{n} \frac{A_{Disposed,Rn}}{CACL_{Rn}} < 1$$	• Ensures calculated peak radiological doses do not exceed the regulatory guidance levels for individuals in the most exposed groups modelled in the post-closure safety assessment. • Ensures compliance with UK Government policy definition of LLW. • Ensures only LLW is disposed of, in compliance with the EASR Permit and as committed by DSRL to the local community.	PC
5.2	**LLW** packages consigned for disposal must have a radioactive content not exceeding 4 GBq/te of alpha or 12 GBq/te of beta/gamma activity*.		
5.3	**Demolition LLW** packages consigned for disposal must have a radioactive content not exceeding 0.01 GB/te of alpha or 0.40 GBq/te of beta/gamma activity*.		
5.4	Non-fixed contamination on the external surfaces of a waste package should be as low as reasonably practicable and in any case less than 0.4 Bq/cm^2 alpha activity and less than 4 Bq/cm^2 beta/gamma activity.	• Ensures safe handling, transportation and disposal operations.	O & T
5.5	The radiation level from the external surface of **containerised LLW** and **non-containerised LLW** accepted for disposal must not exceed 7.5 mSv/hr. **Containerised** and **non-containerised LLW** packages with external radiation levels greater than 2 mSv/hr up and to the limit of 7.5 mSv/hr shall require D3100 ATO Holder approval for disposal. The radiation level from the external surfaces of a **Demolition LLW** package must be less than 2 mSv/hr.	• Ensures safe handling, transport and disposal operations. • Packages with external radiation levels between 2 mSv/hr and 7.5 mSv/hr are subject to special load management arrangements in order to be cautiously protective of members of the public from skyshine exposure.	O, T & PC

WA Rule	Justification and Relevance to Operations (O), Transport (T) and/or Post-closure Environmental Safety (PC)	
6. Criticality safety controls		
6.1 Each Half-Height ISO (HHISO) container of **compacted LLW**, which is restricted to compacted and/or uncompacted 200 litre drums, must comply with the following limits: (i) the beryllium content of each puck/drum must not exceed 100 g; and (ii) the fissile mass of each puck/drum must not exceed 20 g ($^{235}U + 1.7\ ^{239}Pu$); and (iii) the fissile mass of each HHISO must not exceed 600 g ($^{235}U + 1.7\ ^{239}Pu$). Each HHISO container of **mixed LLW,** which comprises solid LLW with no restriction on its physical form, must comply with the following limits: (a) for HHISOs containing less than 100 g of beryllium and less than 10 kg of graphite, the fissile material content must not exceed 115 g ($^{235}U + 1.7\ ^{239}Pu$); or (b) for HHISOs containing less than 100 g of beryllium and less than 50 kg of graphite, the fissile material content must not exceed 100 g ($^{235}U + 1.7\ ^{239}Pu$); or (c) for HHISOs containing less than 1,500 g of beryllium and less than 50 kg of graphite, the fissile material content must not exceed 90 g ($^{235}U + 1.7\ ^{239}Pu$); or (d) for HHISOs containing less than 100 g of beryllium and unlimited graphite, the fissile material content must not exceed 90 g ($^{235}U + 1.7\ ^{239}Pu$). **Non-containerised LLW** items for direct disposal in the LLW vaults must not exceed the **mixed LLW** fissile mass, beryllium and graphite limits applied *pro rata* per 20 m^3 of waste. The fissile mass of **Demolition LLW** must not exceed 6 g ^{235}U per 1 m^3 of waste. 6.2 Exceptions to Rule 6.1 for **LLW** may be agreed in advance through an exception process.	• Ensures criticality safety during transport, disposal operations and the post-closure period.	O, T & PC

WA Rule	Justification and Relevance to Operations (O), Transport (T) and/or Post-closure Environmental Safety (PC)	
7. Quality assurance		
7.1 Prior to disposal, an evidence pack must be compiled providing information to demonstrate that the waste package conforms to the Waste Acceptance Rules.	• To demonstrate that an LLW package conforms to the WA Rules, thus upholding safety during operations, closure and post-closure.	O, T & PC
8. Changes to the Waste Acceptance Rules		
8.1 Any changes to the Waste Acceptance Rules will be through a formal DSRL change control process. 8.2 Any changes to the Waste Acceptance Criteria will be through variation of the EASR Permit.	• To ensure there is no compromise of safety during transport, operations, closure and post-closure.	O, T & PC

* Excluding short-lived daughter radionuclides with half-lives less than 3 months, where those daughters are in secular equilibrium with their parents.

APPENDIX B GRA REGULATORY CROSSWALK

B1 The following table lists the requirements extracted from Chapters 5 through 7 of the GRA [19], provides references to material relevant to meeting these requirements in this ESC and supporting references, and indicates which forward programme items are aimed at further addressing the requirements. The Requirement ID refers to the paragraph in the GRA from which the requirement text is extracted. Where more than one requirement has been extracted from the same paragraph, a letter suffix (a), (b) etc. is used. Where more than one requirement ID number is listed for a requirement, the two identified paragraphs in the GRA provide for essentially the same requirement. The requirement text has been edited from that provided in the GRA to put the wording more into the form of a need placed on the provider of the ESC.

B2 The meaning of the status classification for each requirement is as follows:

- **Addressed** - the requirement is satisfied and no further work is to be undertaken;
- **Addressed/Ongoing** - the requirement has been addressed in this ESC, but the requirement will need to be revisited periodically as the project proceeds;
- **Ongoing** - work to address the requirement has been reported in this ESC, but further work to build confidence or address the requirement is ongoing/anticipated; or
- **Pending** - work to address the requirement has yet to be started.

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
5.2.3	**Requirement R1: Process by agreement.** The developer should follow a process by agreement for developing a disposal facility for solid radioactive waste.	paras. 17-20, Section 12.2	Addressed/ Ongoing	FP.14
5.2.4	Enter into an agreement with the regulator to provide advice and assistance after a decision has been made to start a process to select a site for a disposal facility for solid radioactive waste or, before planning a site investigation programme for a disposal facility at a specific location.	Sections 1.1 and 12.2	Addressed/ Ongoing	FP.14
5.3.1	Apply for authorisation under RSA 93 before any disposal of radioactive waste. An application for an authorisation might be submitted before construction if there is sufficient confidence that an environmental safety case can be made.	Sections 1.1 and 12.2	Addressed	
5.4.3	Agree with the regulator what submissions should be made and when they should be delivered; these will generally be at points in the programme where decisions to invest substantial amounts of time and resources are required.	Section 12.2	Addressed/ Ongoing	FP.14
5.4.4	Provide a forward work programme for review by the regulator. This should identify the proposed work during the next development phase including discussion of how any regulatory issues are to be addressed.	Sections 12.2 and 14	Addressed/ Ongoing	FP.1 - FP.15
5.4.6	The level of detail in the environmental safety case should reflect, for example, the stage of development of the facility, what is known and understood about the selected site, the proposed radioactive waste inventory for disposal and what decision has to be made at the time.	para. 31, Sections 12.3.1 and 12.3.2	Addressed	
5.5.4	Agree the timing and scope of authorisation reviews with the regulator. To support an authorisation review, submit an updated environmental safety case that includes, for example: - knowledge gained during construction and operation of the facility; - new understanding gained from on-going site characterisation work; - results of continuing research and development studies; - experience from similar facilities in other countries; - technological advances in the characterisation, conditioning and packaging of radioactive waste.	Sections 12.2, 12.3.1 and 12.3.2	Addressed	

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
5.5.6	When waste emplacement ends, submit a post-operational environmental safety case to show that the facility can be closed in a way that allows the principles and requirements of the guidance to be met.	para. 198, Section 12.3.2	Pending	FP.14
5.5.7	To support a request for revocation of the authorisation, submit a final environmental safety case to demonstrate that the facility meets the principles and requirements of the guidance. This might be submitted some time after closure of the facility if there is a period of active institutional control.	paras. 700-709, Section 12.3.2	Pending	FP.14
5.5.8	The developer of a near-surface disposal facility might require a Nuclear Site Licence under NIA 65 from HSE. The decision on whether a Nuclear Site Licence is required will be made by HSE.	para. 741	Addressed	Nuclear site licence not needed
5.7.1	**Requirement R2: Dialogue with local communities and others.** The developer should engage in dialogue with the planning authority, local community, other interested parties and the general public on its developing environmental safety case.	Section 12.4	Addressed/ Ongoing	FP.15
5.7.2	The developer is expected to engage widely in discussion of its ESC. Flexible approaches for engaging in discussions are required that adapt to meet a community's needs and expectations.	Section 12.4	Addressed/ Ongoing	FP.15
5.7.3	Consider, in discussion with the relevant local authorities, how to define "local community" for any specific proposal, taking into account the nature, size and location of the proposed facility.	Section 12.4	Addressed	
5.7.5	Work with the regulator to make sure that discussions with the planning authority and local community are open, inclusive and constructive. Technical, social or economic issues that might affect development of a disposal facility should be discussed openly with explanations of what the operator or regulator is doing to deal with these issues. Local communities and others should also be able to challenge the views of the developer and/or regulator on technical and other issues.	Section 12.4 paras. 17, 20	Addressed/ Ongoing	FP.14, FP.15
6.2.1	**Requirement R3: Environmental safety case.** An application under RSA 93 relating to a proposed disposal of solid radioactive waste should be supported by an environmental safety case.	This document para. 14 Section 12.3.1	Addressed/ Ongoing	FP.3 - FP.15

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.2.2 7.1.1 7.2.1(c)	The ESC should demonstrate that the health of members of the public and the integrity of the environment are adequately protected. It will be provided by the developer/operator of the disposal facility and should be designed to demonstrate consistency with the principles set out in Section 4 of this guidance and that the management, radiological and technical requirements set out in Chapter 6 are met.	Sections 4 and 14	Addressed/ Ongoing	FP.3 - FP.15
6.2.3 6.1.3 6.2.7	Meet each management, radiological and technological requirement in the guidance in a manner proportionate to the level of hazard the waste the eventual inventory of waste in the facility will present.	Sections 4 to 14	Addressed/ Ongoing	FP.3 - FP.15
6.2.5	**Requirement R4: Environmental safety culture and management system.** The developer/operator of a disposal facility for solid radioactive waste should foster and nurture a positive environmental safety culture at all times and should have a management system, organisational structure and resources sufficient to provide the following functions: (a) planning and control of work; (b) the application of sound science and good engineering practice; (c) provision of information; (d) documentation and record-keeping; (e) quality management.	Section 12.1	Addressed/ Ongoing	FP.13
6.2.6	Foster and nurture a positive environmental safety culture, i.e. appropriate individual and collective attitudes and behaviours, and require suppliers to do the same. This culture needs to be reflected in and reinforced by the adopted management system.	Section 12.1	Addressed/ Ongoing	FP.13
6.2.8(a)	Implement a management system that includes effective leadership, proper arrangements for policy and decision making, a suitable range of competencies, provision of sufficient resources, a commitment to continuous learning and proper arrangements for succession planning and knowledge management.	Section 12.1	Addressed/ Ongoing	FP.13
6.2.8(b)	The management system should be progressively adapted to provide suitable corporate governance of the organisation over the whole lifecycle of the project, i.e. from the early stages of site investigation onwards until the eventual closure of the disposal facility and any subsequent period of active institutional control.	Section 12.1	Addressed/ Ongoing	FP.13
6.2.9	The written management arrangements supporting the management system should show how, with an appropriate environmental safety culture, environmental safety is directed and controlled. They should also show how the management system is maintained in a living state through regular review, progressive updating and implementation of the management arrangements.	Section 12.1	Addressed/ Ongoing	FP.13

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.2.10	The structure of the developer/operator organisation should be appropriate for its needs including, in particular, its responsibilities for environmental safety. The structure should reflect current and foreseeable operations and should show how key responsibilities are allocated. A new organisation should plan for and establish a structure based on a set of organisational structure principles that are linked to the activities it intends to perform. For an established organisation the structure should remain a 'live' issue, so that it continues to match the business needs and maintains clarity about responsibilities.	para. 719, Figure 12.1	Addressed/ Ongoing	FP.13
6.2.11	The Board, directors and managers of the developer/operator organisation should provide strong leadership to achieve and sustain high standards of environmental safety. In particular, environmental safety messages must be seen to come from the top of the organisation and be embedded throughout its management levels.	paras. 711 – 715	Addressed/ Ongoing	FP.13
6.2.12	The organisation should be capable and forward-looking so as to secure and maintain the environmental safety of the disposal system for the whole of the lifecycle of the disposal facility. Roles, responsibilities, accountabilities and performance standards for environmental safety at all levels should be clear and not conflict with other business roles, responsibilities, accountabilities and objectives.	paras. 711 – 721, Figure 12.1	Addressed/ Ongoing	FP.13
6.2.13	The management system should enable the organisation to develop and maintain the resources and competencies needed to ensure environmental safety. The written management arrangements should show how the organisation achieves and maintains a trained, qualified and experienced workforce that matches the need.	Section 12.1	Addressed/ Ongoing	FP.13
6.2.14	The organisation may need to use contract resource to complement its in-house capability but the implications of this should be recognised for its ability to remain in control in the short term and longer term. The organisation needs to be a capable operator in its own right and able to oversee and manage the work where it uses contractors. Achieving a suitable balance between employee and contractor numbers should take these aspects into account through a resource plan. The organisation will also need a sufficient capability to ensure that goods and services from its suppliers are of a fit and proper standard to meet the requirements of the relevant RSA 93 authorisation and the environmental safety case.	Section 12.1.2	Addressed/ Ongoing	FP.13
6.2.15	Maintain relevant competencies over the lifetime of the facility, including any period of authorisation after closure.	Section 12.1.2	Addressed/ Ongoing	FP.13

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.2.16(a)	Policies and decisions at all levels that affect environmental safety should be rational, objective, transparent and prudent. All relevant considerations need to be taken into account whenever a policy is established or decision is made. New policies and decisions need to relate properly to, and build on, policies already established and decisions already made. Rigorous questioning of all factual material presented and assumptions made should be part of policy and decision making.	paras. 711 – 721	Addressed/ Ongoing	FP.13
6.2.16(b)	Whenever a policy is established or a decision is taken, the reasons for the choice made need to be recorded. The reasons recorded should include the other choices considered and reasons why they were rejected.	para. 718 This document.	Addressed/ Ongoing	FP.3 FP.6 FP.13
6.2.17	Lessons should be learned from internal and external sources to assure continuous improvement in all aspects that affect environmental safety. A learning organisation should challenge accepted established understanding and practice by reflecting on experience to identify and understand the reasons for differences between actual and intended outcomes. The organisation should seek to learn from external sources, including other industries, both in this country and abroad, analysing and acting on the lessons learned.	Section 5 Section 10.2.1 para. 724 Section 12.4	Addressed/ Ongoing	FP.3 FP.4 FP.6 FP.7 FP.8 FP.9 FP.10 FP.11 FP.13 FP.15
6.2.18	Learning should take place throughout the organisation. Staff at all levels should be encouraged to report any actual or potential problems and to make suggestions to avoid or overcome these problems and to achieve improvements generally.	paras. 711 – 715	Addressed/ Ongoing	FP.13
6.2.19	Lessons learned should be embedded through a structured system that is rigorously applied. Reviews should be carried out to confirm that the changes have been made and that they have brought about the desired improvements.	Section 12.1	Addressed/ Ongoing	FP.13
6.2.20	Identify all the key areas in which competency is required and develop a strategy for succession planning and knowledge management in all these areas.	Section 12.1.2	Addressed/ Ongoing	FP.13
6.2.21	Where appropriate, the approaches used to fulfil management system functions should be based on principles derived from national and international standards.	paras. 715, 730	Addressed/ Ongoing	FP.13

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.2.22	The management system needs to be effective in all work that supports the environmental safety case. This covers most of the things that the developer/operator does and includes, at least: investigating the site; designing and constructing the facility; emplacing the waste; closing the facility; and putting in place any arrangements for active institutional control. It also includes work to document these activities and to provide the environmental safety case.	Section 12.1	Addressed/ Ongoing	FP.13
6.2.23	The management system needs to be effective in work that supports the environmental safety case specifically during the period of authorisation. This includes demonstrating compliance with the operational limits and conditions that will be included in the authorisation under RSA 93 held by the facility operator. The operator, through the management system, should monitor and assess radioactive discharges from the facility and levels of radioactivity in the environment, to conduct prospective and retrospective dose assessments and report accordingly.	Sections 4.4, 4.5, 7.9, 10 and 12.1 Appendix A	Addressed/ Ongoing	FP.13
6.2.24	All work that supports the environmental safety case needs to be properly planned and controlled. Any changes need to be made within a well-defined change control procedure, described in the written management arrangements, that assures quality and includes decision-making, doing the work and recording what has been done.	Section 12.1	Addressed/ Ongoing	FP.13
6.2.25	Planning considerations need to include protection against, and mitigation of the effects of, human error and unplanned events during construction, operation and closure (for example accidental flooding), where the environmental safety case might be affected.	Section 5.4 paras. 716-721	Ongoing	FP.4 FP.6 FP.13
6.2.26	All work that supports the environmental safety case needs to apply sound science. Make informed judgements about the quality of the science being applied and make sure that timely scientific investigations are carried out to remedy any deficiencies in understanding of particular relevance. Maintain awareness of scientific developments, both within and outside the UK, that may have a bearing on the environmental safety case for the facility.	Sections 12.1.4, 10.2, and 5	Addressed/ Ongoing	FP.3 FP.6 FP.7 FP.8 FP.10 FP.11
6.2.27	All work that supports the environmental safety case needs to follow good engineering practice.	Sections 5 and 12.1.4	Addressed/ Ongoing	FP.6
6.2.28	Before the decision is made to use a novel technology, carry out trials to demonstrate that any uncertainties about the outcome of using the technology are kept to a minimum.	Section 5	Ongoing	FP.4 FP.6

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.2.29	After the end of the period of authorisation, rely entirely on a combination of engineered measures that can contribute to passive safety (recognising the lifetime for which such features can be expected to remain effective) and natural features and processes.	Sections 3.1, 9.1, and 13	Addressed/ Ongoing	FP.6
6.2.31	All engineered measures will degrade with time and this should be recognised in the environmental safety case.	paras. 370 – 407	Addressed/ Ongoing	FP.6
6.2.34(a)	The developer/operator will be responsible for all information necessary to support the environmental safety case, and will provide it in a timely way within an agreed documentation structure so that its relevance to the environmental safety case is clear.	paras. 732 – 737 Figure 2.4	Addressed/ Ongoing	FP.14
6.2.34(b)	Technical information will need to be submitted in an agreed form that allows the regulator to understand fully the arguments put forward in the environmental safety case and to carry out its own environmental safety assessments to support its judgements.	This document [all supporting references]	Addressed/ Ongoing	FP.14
6.2.37(a)	Set up and maintain a comprehensive system for recording information on all aspects of the project affecting the environmental safety case.	Section 12.1.5	Addressed/ Ongoing	FP.13
6.2.37(b)	Record: decisions taken and the reasons for them, data and results from the site investigation and characterisation programme; design documents, drawings and engineering details of the facility as constructed; records of waste form and characterisation; records of waste emplacements and their location in the facility; other operational information; details of facility closure; and results of monitoring and assessment at all stages of the project.	Section 12.1.5	Addressed/ Ongoing	FP.13
6.2.37(c)	Duplicates of the records will need to be kept at diverse locations and in durable form.	Section 12.1.5	Ongoing	FP.13
6.2.37(d)	At the end of the period of authorisation, make arrangement for the records to be included in the public archive.	paras. 729 and 707-708	Pending	FP.12
6.2.38	The quality management arrangements should be regularly audited internally and from time to time by an external auditor registered by the International Register of Certificated Auditors.	paras. 715, 730	Addressed/ Ongoing	FP.13
6.2.39(a)	Ensure that quality management arrangements are in place to ensure that all information can be traced back to its source.	Sections 12.1.5 and 12.1.6	Addressed/ Ongoing	FP.13
6.2.39(b)	On request, allow access to the original data and information on how they were gathered, so that the regulator can examine the provenance and interpretation of the data.	paras. 725 – 728 [applies to all supporting references in the ESC]	Addressed/ Ongoing	FP.13

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.2.40	Where appropriate, use peer review to supplement other approaches to quality management. The rigour with which peer review is carried out needs to be proportionate to the significance of the work being reviewed to the environmental safety case. The peer review process must not be inappropriately curtailed. There needs to be a clear-cut stage in which the originators of the technical work respond to the reviewers' comments. Provide the comments made by peer reviewers and the responses to those comments to the regulators.	Section 9.3.7 para. 720	Addressed/ Ongoing	FP.13 FP.14
6.3.1	**Requirement R5: Dose constraints during the period of authorisation.** During the period of authorisation, the effective dose from the facility to a representative member of the critical group should not exceed a source-related dose constraint and a site-related dose constraint.	Section 7.7.1 Figure 7.10	Addressed/ Ongoing	FP.8
6.3.2	The following are the maximum doses to individuals which may result from a defined source, for use at the planning stage in radiation protection: - 0.3 mSv per year from any source from which radioactive discharges are made; or - 0.5 mSv per year from the discharges from any single site.	Section 7.7.1 Figure 7.10	Addressed/ Ongoing	FP.8
6.3.3	For the operational and active institutional control phases, consider HPA recommendations that a dose constraint of 0.15 mSv (annual dose) should apply to exposure to the public from a new disposal facility for radioactive waste.	Section 7.7.1 Figure 7.10	Addressed/ Ongoing	FP.8
6.3.4	For comparison with the source-related dose constraint, the assessment of effective dose should take into account both direct radiation from the facility and radiation from current discharges from the facility. For comparison with the site-related dose constraint, the assessment of effective dose should take into account radiation from current discharges from the facility, together with radiation from current discharges from any other sources at the same site (i.e. sources with contiguous boundaries at a single location).	para. 448	Addressed/ Ongoing	FP.8

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.3.5	During the period of authorisation, have a management system in place that provides a level of control on operational discharges that is proportionate to the hazard. In accordance with the authorisation: - monitor and assess radioactive discharges from the facility and levels of radioactivity in the environment; - have plans for action if monitoring suggests an unexpected release from the facility; - put into action remediation plans if any adverse anomalies are identified as a consequence of monitoring; - carry out dose assessments based on the levels of radioactive discharge permitted by the authorisation (prospective assessments) and assessments based on the levels of radioactivity measured in the environment (retrospective assessments); - report this information to the regulator.	Section 10 paras. 711 – 721	Addressed/ Ongoing	FP.11
6.3.7(a)	Show that the controls proposed for the period of active institutional control are sufficient to support the claims made for the period of control and that the arrangements for applying the controls can be relied on to be implemented as planned.	Sections 11 and 7.7.1	Pending	FP.8 FP.12 FP.14
6.3.7(b)	A claim for active institutional control will need to be supported by detailed forward planning of organisational arrangements and a suitable demonstration of funding arrangements.	Section 11	Pending	FP.12 FP.14
6.3.8	Include provisions for site surveillance with scope for remedial work if needed, a programme of environmental monitoring, control of land use and arrangements for the preservation of records. It will need to be supported by evidence that these provisions can be relied on to remain effective throughout the claimed period of time.	Section 11	Pending	FP.12
6.3.10	**Requirement R6: Risk guidance level after the period of authorisation.** 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 (i.e. 1 in a million per year).	Section 7.7.2 Figure 7.10, Figure 7.17, Figure 7.18,	Addressed/ Ongoing	FP.8
6.3.13	Radiological risk associated with a potential exposure situation corresponds to the product of the estimated effective dose that could be received, the estimated probability that this dose will be received and the estimated probability that detriment would occur as a consequence to the person exposed. For comparison with the risk guidance level, assessed risks must be summed over all situations that could give rise to exposure of the same person to radiation.	Section 7.7.2 paras. 378 – 396	Addressed/ Ongoing	FP.8

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.3.14	For situations in which only stochastic effects of radiation exposure need to be considered (i.e. when the estimated annual effective dose is less than 100 mSv and the estimated equivalent dose to each tissue is below the relevant threshold for deterministic effects), a risk coefficient of 0.06 per Sv should be used.	para. 450	Addressed/ Ongoing	FP.8
6.3.16	If the estimated effective dose received over the period of a year or less is greater than 100 mSv it should not be combined with the probability of receiving the dose to give an estimated risk but the dose and probability should be presented separately.	Section 7.7.2, but this is not applicable as no estimated effective doses are greater than 100 mSv	Addressed	
6.3.19	Demonstrate that the measure chosen for comparison with the risk guidance level is reasonable (e.g. expectation (mean) value of risk) and present information about the sensitivity of the chosen measure to important parameter values.	para. 450, Section 7.7.3	Addressed/ Ongoing	FP.8
6.3.21	In setting up a risk assessment, aim for data and assumptions that represent realistic or best estimates of the system behaviour. However, where the data do not support this approach or where the assessment can usefully be simplified, conservative data and assumptions to be conservative can be chosen as long as the requirements are still shown to be met.	Section 7.2.3	Addressed/ Ongoing	FP.8
6.3.22	In cases where the hazard presented by the waste warrants a detailed assessment of risks, present a probability distribution of dose covering the range of possible doses that a person representative of each potentially exposed group may receive and will provide the probability that this person receives any given dose. The probability distribution will vary with time into the future.	Section 7.7.2	Addressed/ Ongoing	FP.8
6.3.26(a)	Quantifiable uncertainties should be considered within a numerical risk assessment developed as part of an environmental safety case.	Section 7.2.3 and 7.7.3	Addressed/ Ongoing	FP.8
6.3.26(b)	Unquantifiable uncertainties (where, for example, it is not possible to acquire relevant data, or if acquiring enough data to evaluate the uncertainty statistically could only be done at disproportionate cost) need to be taken into account in developing the safety case, but should be kept apart from the quantifiable uncertainties and given separate consideration. Taking into account unquantifiable uncertainties will inevitably involve judgement, first identifying significant unquantifiable uncertainties and then considering 'balance of likelihood'.	Section 7.2.3 paras. 468 – 481	Addressed/ Ongoing	FP.8

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.3.28	For highly uncertain future events, consider whether it is appropriate to undertake numerical risk assessments for comparison with the risk guidance level (e.g. “what-if” scenarios and human actions that affect the disposal system).	Section 7.2.3	Addressed/ Ongoing	FP.8
6.3.30	Consider different groups of people that could be at risk of exposure (potentially exposed groups) in order to identify a person representative of those people at greatest risk at a given time.	paras. 415 – 430	Addressed/ Ongoing	FP.8
6.3.31(a)	Substantiate the choice of potentially exposed groups as being reasonable and suited to the particular circumstances. The location and characteristics of the groups considered should be based on the assessed releases of radioactivity and on assumptions about changing environmental conditions.	paras. 419 – 425	Addressed/ Ongoing	FP.8
6.3.31(b)	The habits and behaviour assumed for people in potentially exposed groups should be based on present and past habits and behaviour that have been observed and that are judged relevant. Metabolic characteristics similar to those of present-day populations should be assumed.	para. 441	Addressed/ Ongoing	FP.8
6.3.31(c)	Other parameters (i.e. non-behavioural and metabolic) used to characterise a representative member of a potentially exposed group should be generic enough to give confidence that the assessment of risk will apply to a range of possible future populations.	paras. 415 – 430	Addressed/ Ongoing	FP.8
6.3.32	If two or more separate disposal facilities present significant risks to the same potentially exposed groups, consideration should be given to the combined risks.	para. 448 – 449	Addressed	
6.3.35	If there is a significant discrepancy between the results of a risk assessment and the risk guidance level, or if the probability distribution of dose at some future time is of concern, additional information should be provided to demonstrate that an appropriate level of environmental safety is assured.	Sections 7.2.3 and 9	Addressed/ Ongoing	FP.8

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.3.36	**Requirement R7: Human intrusion after the period of authorisation.** The developer/operator of a near-surface disposal facility should assess the potential consequences of human intrusion into the facility after the period of authorisation on the basis that it is likely to occur. The developer/operator should, however, consider and implement any practical measures that might reduce the chance of its happening. The assessed effective dose to any person during and after the assumed intrusion should not exceed a dose guidance level in the range of around 3 mSv/year to around 20 mSv/year. Values towards the lower end of this range are applicable to assessed exposures continuing over a period of years (prolonged exposures), while values towards the upper end of the range are applicable to assessed exposures that are only short term (transitory exposures).	paras. 468 – 474 (Section 7.7.2), Figure 7.16	Addressed/ Ongoing	FP.8
6.3.39	Assess potential exposures of possible intruders to the radiological dose that might arise form a ranges of possible exposure scenarios. These scenarios should consider the exposures that arise from the potential exposures from the inventory of waste to be disposed of including any gaseous emissions from the waste such as radon; this should not include exposures to naturally occurring radon. Due to the large uncertainties associated with exposures to radon the developer should present these both aggregated with other exposures and individually.	paras. 463 – 474 paras. 383 – 389 Figure 7.16	Addressed/ Ongoing	FP.8
6.3.40	Show that dose thresholds for severe deterministic injury to individual body tissues are unlikely to be exceeded as a result of human intrusion into a near-surface disposal facility.	para. 418 (not applicable / dose thresholds not exceeded)	Addressed	
6.3.41(a)	Do not consider human intrusion where the intruders have full knowledge of the existence, location, nature and contents of the disposal facility.	para. 349	Addressed	
6.3.41(b)	Consider human intrusion in cases where there is no prior knowledge of the disposal facility or where there is knowledge of the existence of underground workings but no understanding what they contain.	paras. 383 – 389	Addressed/ Ongoing	FP.8
6.3.44	Where barriers that provide environmental safety functions are natural, rather than engineered, consider how far from the disposal facility itself it is reasonable to apply the dose guidance level rather than the risk guidance level.	paras. 478 – 480	Addressed/ Ongoing	FP.8

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.3.45	Consider, and implement, any practical measures that might reduce the likelihood of human intrusion. Such measures should not compromise the environmental safety performance of the disposal system if human intrusion does not occur. The measures to reduce the likelihood of human intrusion should be considered as part of option studies under Requirement R8, Optimisation.	para. 204 paras. 146 – 154	Addressed/ Ongoing	FP.6
6.3.47	Explore the timing, type and extent of human intrusion into a facility through one or more 'what-if' scenarios, separate from the scenarios representing evolution of the disposal system undisturbed by human intrusion.	paras. 468 – 474	Addressed/ Ongoing	FP.8
6.3.48(a)	Human intrusion scenarios should be based on human actions that use technology and practices similar to those that currently take place, or that have historically taken place, in similar geological and geographical settings anywhere in the world. The assumed habits and behaviour of people should be based on present and past human habits and behaviour that have been observed and are judged relevant.	paras. 383 – 389	Addressed/ Ongoing	FP.8
6.3.48(b)	Human intrusion scenarios should include all human actions associated with any material removed from the facility, including considering what is then done with this material. When considering optimisation, the number of people involved in actions associated with intrusion should be assessed, and may be assumed to be similar to the typical number involved in similar actions now or historically. Similarly, the number of people who might be exposed as a result of occupying the site or neighbourhood after the intrusion should also be assessed. Each scenario considered should be substantiated as being reasonable and suited to the particular circumstances.	paras. 383 – 389 para. 438	Addressed/ Ongoing	FP.8
6.3.49	Present assessments of radiation doses to individuals representative both of those undertaking intrusive activities and those who might occupy the site or the neighbourhood after intrusion. Explore the consequences of intrusion in a wider geographical sense and on the long-term behaviour of the disposal system. The assessments should take into account all radionuclides that may be present in the waste and all decay products making a significant contribution to dose. They should also take into account inhomogeneities in the waste.	para. 438 para. 444 paras. 468 – 474 para. 501 – 504	Addressed/ Ongoing	FP.8
6.3.50	Present assessments of the radiation doses received by non-human organisms as a result of human intrusion into the facility and demonstrate that these are not at a level liable to cause significant harm to populations of such organisms.	Section 7.9	Addressed/ Ongoing	FP.8

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.3.51	Use the results from human intrusion scenarios as part of option studies under Requirement R8, Optimisation to reduce the radiological impacts resulting from human intrusion, subject to balancing all the other considerations relevant to optimisation.	Section 5.5	Addressed/ Ongoing	FP.6
6.3.52	Where potential doses around the dose guidance level may be possible for human intrusion scenarios as a result of long-lived radionuclides, use the results of the scenarios to propose facility-specific authorisation limits and conditions, such as inventory limits and allowable activity concentrations, supported with suitable arguments.	paras. 468 – 474 (not applicable / no such doses are calculated)	Addressed	
6.3.54	Where there is a difference between practical measures to reduce the likelihood or consequences of disruption and what can reasonably be claimed in the ESC (because of uncertainties surrounding human intrusion), the operator/developer may be required to adopt practical measures that go beyond what is accepted as a substantiated claim in the ESC.	Section 11	Addressed/ Ongoing	FP.12
6.3.55	Show that intrusion by non-human species, including plant species (for example tree roots), is not a significant issue.	para. 390	Addressed/ Ongoing	FP.8
6.3.56	**Requirement R8: Optimisation.** The choice of waste acceptance criteria, how the selected site is used and the design, construction, operation, closure and post-closure management of the disposal facility should ensure that radiological risks to members of the public, both during the period of authorisation and afterwards, are as low as reasonably achievable (ALARA), taking into account economic and societal factors.	Section 5.5 para. 750	Addressed/ Ongoing	FP.6
6.3.59	To succeed, optimisation requires good communication, both within the developer/operator's own organisation and with supplier organisations, as well as with the regulators and the local community.	Section 5.5 paras. 711 – 721 paras. 743 – 746	Addressed/ Ongoing	FP.6
6.3.60	Where there are choices to be made among significantly different alternatives, carry out options studies. Present the results to the regulators and make them publicly available.	Section 5.5	Addressed/ Ongoing	FP.6 FP.8
6.3.62	Optimisation needs to be considered at each decision-making stage. Once a decision has been implemented, it forms part of the framework within which further decisions, and the optimisation considerations that go with them, must be made. Even when a decision has apparently been made, it continues to represent an uncertainty before it has been implemented. The end of the period of authorisation is the end of decision-making by the developer/operator.	Section 5.5	Addressed/ Ongoing	FP.6

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.3.64	In the presence of uncertainties, the main optimisation task is to make sure that an acceptable situation will result, not only in likely future circumstances, but also in circumstances that are possible but unlikely. Acceptability can be measured in terms of radiation dose or risk, but it will often be unnecessary to go as far as calculating these quantities to recognise a situation as unacceptable.	Section 5.5	Addressed/ Ongoing	FP.6
6.3.65	Once the main optimisation task has been fulfilled, follow the more usual path of finding the best way forward for each set of circumstances. At this stage, focus mainly on the likely circumstances. Unlikely circumstances should not have undue influence on design, construction or operation.	Section 5.5	Addressed/ Ongoing	FP.6
6.3.66	Favour a simple approach to optimisation rather than a more complex one, where either would deliver an adequate outcome. If a numerical approach is used to compare options, recognise that the size of the population at risk is a relevant issue as well as the magnitude of individual risks.	Section 5.5	Addressed/ Ongoing	FP.6
6.3.67	At each decision-making stage, provide a written record of the consideration of optimisation. As part of the environmental safety case, provide a historical record of the decisions taken and implemented, and the optimisation considerations that related to those decisions when they were taken.	Section 5.5	Addressed/ Ongoing	FP.6
6.3.69	Calculate collective doses and ‘group’ doses only for times where they can be a useful discriminator between different waste management options. This is likely to be of the order of several hundred years post-closure but the exact length of time will be dependent on the waste disposed of and type of facility and is not likely to be very long term in view of the large uncertainties.	para. 555	Addressed/ Ongoing	FP.10
6.3.70 7.3.35	**Requirement R9: Environmental radioactivity.** The developer/operator should carry out an assessment to investigate the radiological effects of a disposal facility on the accessible environment both during the period of authorisation and afterwards with a view to showing that all aspects of the accessible environment are adequately protected.	Section 7.9 paras. 643 – 651	Addressed/ Ongoing	FP.8 FP.10
6.3.74	Carry out an assessment and draw conclusions about the effects of a disposal facility on the accessible environment using the best available information at the time of the assessment. Provide this assessment as an integral part of the environmental safety case and update it as new information becomes available and when other parts of the case are updated. The extent and complexity of the assessment should be proportionate to the radiological hazard presented by the waste in the facility.	Section 7.9 paras. 643 – 651	Addressed/ Ongoing	FP.8 FP.10

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.3.75	The assessment of effects on the accessible environment should include an assessment of effects after human intrusion, making the same human intrusion assumptions as when assessing the effects on people.	para. 540	Addressed/ Ongoing	FP.8
6.4.1 7.3.36	**Requirement R10: Protection against non-radiological hazards.** The developer/operator of a disposal facility for solid radioactive waste should demonstrate that the disposal system provides adequate protection against non-radiological hazards.	Sections 7.10 and 4.3.5 para. 183	Addressed/ Ongoing	FP.6
6.4.2	A level of protection should be provided against non-radiological hazards that is no less stringent than would be provided if national standards for disposing of waste that presents non-radiological hazards but not a radiological hazard were applied.	Section 7.10 para. 183	Addressed/ Ongoing	FP.6
6.4.4	Optimisation only applies to radiological risks, but adequate protection against non-radiological hazards needs to be maintained when optimising for radiological risks.	Section 5.5	Addressed/ Ongoing	FP.6
6.4.5	The environmental safety case should demonstrate that adequate protection against non-radiological hazards is achieved, using methods and approaches suited to the nature and proportionate to the magnitude of the hazards and suited to the characteristics of the disposal system.	Sections 7.10 and 4.3.5 para. 183	Addressed/ Ongoing	FP.6
6.4.6	**Requirement R11: Site investigation.** The developer/operator of a disposal facility for solid radioactive waste should carry out a programme of site investigation and site characterisation to provide information for the environmental safety case and to support facility design and construction.	Section 6	Addressed/ Ongoing	FP.7 FP.11
6.4.7	Establish a proportionate approach to site investigation that uses some or all of the results from site characterisation, modelling studies, design and construction to guide investigations. The site investigation should be presented as part of a structured programme that provides the requisite information for the environmental safety case.	Section 6.4	Addressed/ Ongoing	FP.7
6.4.8(a)	Show that the geological environment is characterised, understood and can be analysed to the extent necessary to support the environmental safety case. This will involve considering, for example, the lithology, the stratigraphy, the geochemistry, the local and regional hydrogeology, and the resource potential of the area.	Section 6	Addressed/ Ongoing	FP.7
6.4.8(b)	Assess the potential for, and effects of, dynamic processes such as seismic events and ground subsidence.	Section 6.3 paras. 475 – 481	Addressed/ Ongoing	FP.8 FP.7

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.4.9(a)	The biosphere is characterised, understood and capable of analysis to the extent necessary to support the environmental safety case. This may involve consideration of, for example, topography, soils, surface water systems, flora and fauna distributions and human settlement patterns and activities.	Section 6.2.1 paras. 415 – 430	Addressed/ Ongoing	FP.7 FP.8 FP.11
6.4.9(b)	The investigation and characterisation of the biosphere should be sufficiently comprehensive to support calculations of dose during the period of authorisation and should be proportionate to the assumptions made in the environmental safety case for calculating risks after the period of authorisation.	paras. 415 – 430	Addressed/ Ongoing	FP.7 FP.8 FP.11
6.4.10(a)	Show that the geological, hydrogeological and other characteristics of the region and the site under present and reasonably foreseeable future conditions will allow the environmental safety case for the facility to be made.	Sections 7.7.1 and 7.7.2	Addressed/ Ongoing	FP.7 FP.8
6.4.10(b)	Consider features and properties of the site related to release and transport of radionuclides in the gas phase.	paras. 431 – 437 paras. 463 – 467 paras. 181 – 182	Addressed/ Ongoing	FP.7 FP.8
6.4.11	Identify the presence of any actually or potentially valuable resources near the site and make an assessment of the extent to which the site and its surroundings might be disturbed as a result. Consider the implications for the integrity of the disposal system.	para. 385 Section 6.2.6	Addressed/ Ongoing	FP.7 FP.8
6.4.13	Before carrying out any intrusive geological investigations, assess the extent to which these might disturb the site and any implications this might have for the environmental safety case.	Section 6.4	Addressed/ Ongoing	FP.7
6.4.14	Site characterisation should involve investigating specific properties of the site and its surroundings in sufficient detail to support the environmental safety case and may include the following: - Local and regional borehole investigations. - Characterisation of soil layers and quaternary deposits. - Characterisation of surface waters and sediments. - Characterisation of surface and sub-surface flora, fauna and ecosystems. - Development of regional and local geological, geotechnical, hydrogeological and geochemical understanding. - Development of the environmental baseline prior to facility construction - Where relevant, consideration of the need to include a phase of underground investigation within the body of the host rock for the proposed disposal facility.	Section 6.4	Addressed/ Ongoing	FP.7 FP.11

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.4.15	Depending on the hazard presented by the waste to be disposed of, adopt an iterative approach to facility design and development of the environmental safety case as results are progressively obtained from the site characterisation activities.	Section 5.1.3	Addressed/ Ongoing	FP.6
6.4.16	**Requirement R12: Use of site and facility design, construction, operation and closure.** The developer/operator of a disposal facility for solid radioactive waste should make sure that the site is used and the facility is designed, constructed, operated and capable of closure so as to avoid unacceptable effects on the performance of the disposal system.	Section 5.2 – 5.4	Addressed/ Ongoing	FP.6
6.4.17	The approach to the use of the site and to facility design, construction, operation and closure should be proportionate to the hazard presented by the waste that the facility is intended to receive.	Section 5.1.3	Addressed/ Ongoing	FP.6
6.4.18	Demonstrate that the proposed location of the facility within the site is large enough to accommodate the categories and quantities of waste to be disposed of, whilst being far enough away from geological media of less suitable characteristics.	Section 5.2.1 and 5.2.2	Addressed/ Ongoing	FP.6 FP.7
6.4.19	Show that the methods of construction of the facility are consistent with the claims made in the environmental safety case, in that they do not unduly disturb the geological environment and the containment properties of the host rock.	Section 5.3	Addressed/ Ongoing	FP.6 FP.7
6.4.20(a)	Show that the geological conditions in each section of the disposal facility, as disturbed by construction, are suitable for the types and quantities of waste that it is proposed to dispose of in that section.	Sections 6.1, 6.2 and 6.4	Addressed/ Ongoing	FP.7 FP.6
6.4.20(b)	Where backfilling is used, show that methods and materials have been chosen that are compatible with the waste form and the geological setting, and that provide an overall system performance consistent with the claims made in the environmental safety case.	Section 5.2.4 para. 180	Addressed/ Ongoing	FP.6 FP.7
6.4.21	In design and construction, take into account a number of effects that may arise from properties of the waste, including: - gas generation through microbial, chemical, or radiolytic action, or as a result of radioactive decay; - heat generation through microbial or chemical action, or as a result of radioactive decay; - criticality through concentration of fissile nuclides (for near-surface facilities, this can probably be dealt with by a simple analysis).	Sections 5.2.10, 5.2.12 and 5.2.13, 7.11	Addressed/ Ongoing	FP.6 FP.3

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.4.22	Gas generation within the disposal facility can lead to gas movement through and around the facility. Considerations will need to include any venting of gases, both those presenting a radiological hazard and those presenting other hazards such as explosions or asphyxiation, to the atmosphere that may occur and any implications this may have for people and the environment	Section 5.2.10	Addressed/ Ongoing	FP.6
6.4.23	Make plans for corrective action to deal with foreseeable geological or geotechnical problems which might arise during construction, operation or closure.	Sections 5.3 and 5.4	Addressed/ Ongoing	FP.7
6.4.24	At the design stage, and periodically during the lifetime of the facility, demonstrate that it is able satisfactorily to close the disposal facility and, where relevant, seal any preferential pathways that will or may be introduced as a result of the siting, construction and operation of the disposal facility.	paras. 177 – 190, 198	Addressed/ Ongoing	FP.6 FP.8
6.4.25	For facilities that are not regulated under the landfill regulations and not owned by a public sector body such as NDA, ensure that suitable financial provision has been and is being made such that the obligations (including any aftercare obligations) arising from the authorisation are being and will continue to be fulfilled.	para. 199 (funding provided each year by the NDA)	Addressed	
6.4.26 6.4.27	**Requirement R13: Waste acceptance criteria.** The developer/operator of a disposal facility for solid radioactive waste should establish waste acceptance criteria consistent with the assumptions made in the environmental safety case and with the requirements for transport and handling, and demonstrate that these can be applied during operations at the facility.	Section 4.4, Appendix A	Addressed/ Ongoing	FP.3 FP.4
6.4.28	Include in the acceptance criteria the factors that affect the performance of the waste before and after disposal, including the radionuclide content, the chemical and physical form and durability, the susceptibility to microbial action, the thermal and radiation stability, and the mechanical stability.	Section 4.4, Appendix A	Addressed/ Ongoing	FP.3 FP.4 FP.8

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.4.29(a)	Include requirements in the acceptance criteria that ensure as far as reasonably practicable that all waste accepted for disposal is passively safe. The chemical and physical form of the waste should limit detrimental chemical or microbial interactions, and should restrict the release of radionuclides into the disposal environment, in accordance with the assumptions of the environmental safety case. The radiation and heat resistance of the waste form should be in accordance with the assumptions of the environmental safety case. The waste package should have sufficient mechanical stability to withstand the conditions of transport and handling, and to meet any assumptions regarding structural integrity made in the case.	Section 4.4, Appendix A	Addressed/ Ongoing	FP.3 FP.4 FP.8
6.4.29(b)	Demonstrate that the possibility of a local accumulation of fissile material, such as to produce a neutron chain reaction, will not arise.	Section 7.11	Addressed/ Ongoing	FP.3 FP.4
6.4.30	Make sure that the radionuclide content and composition, including the fissile content, of waste consignments received for disposal are sufficiently well characterised to comply with the conditions of the authorisation under RSA 93.	Sections 4.3 and 7.11	Addressed/ Ongoing	FP.3
6.4.31	**Requirement R14: Monitoring.** In support of the environmental safety case, the developer/operator of a disposal facility for solid radioactive waste should carry out a programme to monitor for changes caused by construction, operation and closure of the facility.	Section 10	Addressed/ Ongoing	FP.11
6.4.32	Establish a reasoned and proportionate approach to a programme for monitoring the site and facility. This monitoring should provide data during the period of authorisation to ensure that the facility is operating within the parameters set out in the environmental safety case. However, the monitoring must not itself compromise the environmental safety of the facility.	Section 10	Addressed/ Ongoing	FP.11
6.4.33	Carry out monitoring during the investigation and pre-construction stages to provide a baseline for monitoring at later stages. The same measurements may form part of the site investigation programme. They should include measurements of pre-existing radioactivity in appropriate media, together with geological, physical and chemical parameters which are relevant to environmental safety and which might change as a result of construction and waste emplacement (for example groundwater properties such as pressures, flows and chemical composition).	Section 10	Addressed/ Ongoing	FP.11

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
6.4.34	Undertake radiological monitoring and assessment during the period of authorisation to provide evidence of compliance with authorised discharge limits and assurance of radiological protection of members of the public. In addition, during the construction stage and the period of authorisation, monitor non-radiological parameters to confirm understanding of the effects that construction, operation and closure of the facility have on the characteristics of the site. In particular, demonstrate that changes in, and evolution of, the parameters monitored are consistent with the environmental safety case.	Section 10	Addressed/ Ongoing	FP.11
6.4.35	Carry out appropriate investigation and monitoring during the construction stage and period of authorisation to establish: the characteristics of the site; the behaviour of the disposal system; and the extent of disturbance caused by intrusive site investigation procedures and by construction, operation and closure of the facility.	Sections 6.4 and 10	Addressed/ Ongoing	FP.7 FP.11
6.4.36	The monitoring programme should clearly to set out the levels of specific contaminants that will trigger action. It should include an action plan to deal with possible contamination from the facility and an approach to confirming any apparently positive results to avoid inappropriate action being taken in the event of a false positive observation.	Section 10	Addressed/ Ongoing	FP.11
6.4.37	Assurance of environmental safety must not depend on monitoring or surveillance after the declared end of the period of authorisation. Subsequent monitoring that the developer/operator may wish to include is not ruled out, provided it does not produce an unacceptable effect on the environmental safety case.	Sections 3.1 and 10 para. 752	Addressed/ Ongoing	FP.11
7.1.2	Provide an environmental safety case that responds to the guidance set out in a manner proportionate to the radiological hazard presented by the waste.	This document Section 12.3.1	Addressed/ Ongoing	FP.1 - FP.15
7.1.3	If the disposal facility is on a nuclear licensed site, provide a nuclear safety case for the facility that meets the requirements of HSE. The nuclear safety case will have different objectives from the environmental safety case. The arguments presented in the two separate safety cases will need to be compatible.	para. 741 (nuclear site licence not needed)	Addressed	
7.2.1(a)	The environmental safety case should demonstrate a clear understanding of the disposal facility in its geological setting (“the disposal system”) as it evolves.	Sections 7.3, 7.4, 7.5.1 and 7.5.2	Addressed/ Ongoing	FP.8
7.2.1(b)	The environmental safety case needs to show how the various components of the disposal system contribute to meeting the requirements.	Section 9.1 Table 5.1	Addressed/ Ongoing	FP.8 FP.6

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
7.2.2	The environmental safety case should include an environmental safety strategy supported by detailed arguments to demonstrate environmental safety. The environmental safety strategy should present a top level description of the fundamental approach taken to demonstrate the environmental safety of the disposal system. It should include a clear outline of the key environmental safety arguments and say how the major lines of reasoning and underpinning evidence support these arguments.	Sections 3.1, 9, 12.3.1 and 13	Addressed/ Ongoing	FP.8
7.2.3	The environmental safety case should demonstrate, using a structure based on clear linkages, how the environmental safety strategy is supported by the detailed arguments and how the arguments are supported by evidence, analysis and assessment. Internal consistency within the environmental safety case needs to be established and maintained.	Sections 9 and 12.3.1	Addressed/ Ongoing	FP.8
7.2.4	The environmental safety case should explain how uncertainties have been considered and will be managed in the future and demonstrate that there can be confidence in the environmental safety case notwithstanding the uncertainties that remain. It should also demonstrate that potential biases and their effects on the environmental safety case have been identified and eliminated or minimised.	Sections 7.2.3, 7.3, 7.4 and 7.7.3 para. 721	Addressed/ Ongoing	FP.7 FP.8 FP.10
7.2.5	Everything significant that is claimed or assumed in the environmental safety case should be supported by evidence that is adequate in content and is of appropriate type or types, detail and robustness.	paras. 342 – 344 paras. 725 – 731 ESC References	Addressed/ Ongoing	FP.7 FP.8 FP.10
7.2.6(a)	The ESC should describe all aspects that may affect environmental safety, including the geology, hydrogeology and surface environment of the site.	Sections 6.1, 6.2, 7.4.2, 7.4.3, 7.5.1 and 7.5.2	Addressed/ Ongoing	FP.7 FP.8
7.2.6(b)	The ESC should describe all aspects that may affect environmental safety, including the characteristics of the waste (including any waste treatment and conditioning before disposal).	Section 4.3	Addressed/ Ongoing	FP.3 FP.8
7.2.6(c)	The ESC should describe all aspects that may affect environmental safety, including the design of the facility and the techniques used to construct, operate and close it.	Sections 5.2, 5.3 and 5.4	Addressed/ Ongoing	FP.6
7.2.7	To an extent appropriate to the radiological hazard presented by the waste, the environmental safety case should make use of multiple lines of reasoning based on a variety of evidence, leading to complementary environmental safety arguments. The evidence may be both qualitative and quantitative, supported where appropriate by robust numerical analyses. The reasoning and assumptions should be clear and the evidence supporting them traceable.	Section 9	Addressed/ Ongoing	FP.8 FP.10

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
7.2.8(a)	The environmental safety case should include quantitative environmental safety assessments for both the period of authorisation and afterwards. These assessments will need to extend into the future until the radiological risks have peaked or until the uncertainties have become so great that quantitative assessments cease to be meaningful.	Section 7.4.3	Addressed/ Ongoing	FP.8
7.2.8(b)	Show how radionuclides might be expected to move from the wastes through the immediate physical and chemical environment of the disposal facility and through the surrounding geological formations into and through the environment.	para. 636 Section 7.7	Addressed/ Ongoing	FP.7 FP.8 FP.10
7.2.8(c)	After the period of authorisation and while any significant hazard remains, the environmental safety case should explore the consequences not only of the expected evolution of the disposal system, but also of less likely evolutions and events.	Section 7.2.3 paras. 468 – 481	Addressed/ Ongoing	FP.8
7.2.9	The environmental safety case should describe the arguments for having confidence in the case including, for example, reference to: - the quality and robustness of the quantitative safety assessment and consideration of uncertainty; - the quality, robustness and relevance of the other arguments and evidence presented; - the developer/operator's environmental safety culture and the breadth and depth of expertise and experience of individuals involved in activities supporting the ESC; - the main features of the developer/operator's management system, such as planning and control of work, the use of sound science and good engineering practice, record-keeping, quality management and peer review.	Sections 9 and 12.1	Addressed/ Ongoing	FP.10 FP.13
7.2.10(a)	The environmental safety case should describe and substantiate the level of protection provided by the disposal system both during the period of authorisation and in the long term. It should be sufficiently comprehensive and robust to provide adequate confidence in the environmental safety of the disposal system bearing in mind the radiological hazard presented by the waste.	Section 9.2	Addressed/ Ongoing	FP.8 FP.10
7.2.10(b)	Be alert to possible future changes to standards and to basic data, and make the environmental safety case as robust as reasonably practicable in this respect.	Section 12.3.2	Addressed/ Ongoing	FP.14
7.2.12	Provide/update the environmental safety case at each step during the development of a disposal facility and at suitable intervals during the period of authorisation to inform and support regulatory decisions in a timely manner.	Section 12.3.2 para. 760	Addressed/ Ongoing	FP.14

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
7.2.13	Updates to the environmental safety case should reflect growing knowledge about the site and should increasingly reflect the disposal facility as built and wastes as disposed of rather than as anticipated. Updates should also take into account, for example, feedback from regulators and feedback from other relevant facilities, both nationally and internationally, together with developments in environmental safety assessment techniques, in radiological protection and in technical understanding more generally. The eventual aim will be to show that the disposal system as finally realised in practice will provide proper protection to people and the environment.	paras.721, Sections 6 and 12.3.2	Addressed/ Ongoing	FP.14 FP.7
7.2.14	Consider how the safety case documentation will be structured and updated to promote traceability between steps and transparency. Maintain a detailed audit trail for changes to the environmental safety case and documentation.	paras. 732 – 740 Report History	Addressed/ Ongoing	FP.14
7.2.15	Present the environmental safety case in a way that people will understand. Different styles and levels of documentation are likely to be needed to present the environmental safety case to different audiences, but these should be consistent in referring to the same fundamental arguments.	paras. 743 – 746	Addressed/ Ongoing	FP.15
7.2.16	Throughout the development and period of authorisation of the facility, preserve the environmental safety case documentation and all relevant records and provide access to these by interested parties.	Section 12.1.5 paras. 735, 743 – 746	Addressed/ Ongoing	FP.14 FP.15
7.2.17(a)	The environmental safety case should be used to help specify a forward programme of improvement work, both to the environmental safety case itself and more broadly.	Section 14	Addressed/ Ongoing	FP.1 - FP.15
7.2.17(b)	Operational decisions and practices should be consistent with the environmental safety case.	Section 5.5	Addressed/ Ongoing	FP.6 FP.8
7.2.18(a)	The environmental safety case will provide an input to deriving facility-specific regulatory limits and conditions, and should help to underpin the developer/operator's waste acceptance criteria and emplacement requirements.	Sections 4.4, 7.10, 7.11, and 8	Addressed/ Ongoing	FP.3 FP.8 FP.4
7.2.18(b)	The environmental safety case may help to guide the monitoring of discharges for compliance with the authorisation, and the environmental monitoring programme for the site and the surrounding area.	Section 10.2	Addressed/ Ongoing	FP.11
7.3.2	The disposal system will consist of multiple components or barriers. There is a distinction between these components and the environmental safety functions they provide.	paras. 631 – 641 Table 5.1	Addressed/ Ongoing	FP.8 FP.10

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
7.3.3(a)	The environmental safety case should include an explanation of, and substantiation for, the environmental safety functions provided by each part of the system. It should also identify which radionuclides each function is relevant to and the expected time period over which the function is effective.	paras. 631 – 641 Table 5.1	Addressed/ Ongoing	FP.8 FP.10
7.3.3(b)	The environmental safety case for the period after closure of a disposal facility should not depend unduly on any single function.	paras. 631 – 641	Addressed/ Ongoing	FP.8
7.3.4	Explore the contribution that each environmental safety function makes to the environmental safety case (for example, by sensitivity analyses). Explore the circumstances where more than one function is impaired.	paras. 631 – 641 Section 7.7	Addressed/ Ongoing	FP.8
7.3.5	Provide one or more quantitative assessments aimed at calculating risk, which can then be compared to the risk guidance level, as a key part of the environmental safety case for times after the period of authorisation.	Section 7.7.2	Addressed/ Ongoing	FP.8
7.3.6 7.3.19	Where environmental safety needs to be assured over very long timescales, use multiple lines of reasoning based on a variety of evidence, leading to complementary environmental safety arguments. In the overall environmental safety case, these complementary arguments need to be brought together in a structured way.	Sections 9.1, 9.2 and 13	Addressed/ Ongoing	FP.10 FP.8
7.3.7(a)	Examples of environmental safety indicators that might be used to strengthen the environmental safety case include radiation dose, radionuclide flux, radionuclide travel times, environmental concentration and radiotoxicity.	Section 9.2	Addressed/ Ongoing	FP.10
7.3.7(b)	Where the radiological hazard presented by the waste warrants it, provide a wide range of information, for example: - assessments of radionuclide release characteristics from the waste and from the various barriers that make up the disposal system; - assessments of the concentrations in the accessible environment of radionuclides released from the disposal system and comparison of these with naturally occurring levels of radioactivity in the environment; - where appropriate, assessment of collective radiological impact (as a measure of how widespread any significant increase in risk may be as a result of radioactivity released into the accessible environment); - unifying statements that aim to place in context the different items of information that contribute to assuring environmental safety.	Sections 7.7, 7.13, 9.2 and 13 Figure 9.1 Figure 9.6	Addressed/ Ongoing	FP.8 FP.10

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
7.3.8	Account for uncertainties explicitly, analyse their possible consequences and consider where they may be reduced or their effects lessened or compensated for. Uncertainties themselves are not obstacles to establishing the environmental safety case, but they do need proper consideration and including in the structure of the environmental safety case as appropriate.	Sections 7.2.3 and 7.7.3 para. 721	Addressed/ Ongoing	FP.8 FP.10 FP.7
7.3.10	Demonstrate that the environmental safety case, for both the period of authorisation and afterwards, takes 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; - 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.	Sections 7.7.3 and 9.3 para. 721	Addressed/ Ongoing	FP.8 FP.10 FP.7 FP.11
7.3.11	Provide explanations for interested parties of the significance of uncertainties important to the environmental safety case, by presenting these explanations in a way that people will understand.	Section 12.4	Addressed/ Ongoing	FP.15
7.3.12	Account for both readily quantifiable and unquantifiable uncertainty types in the environmental safety case.	Sections 7.2.3, 7.7.2 and 7.7.3 para. 721	Addressed/ Ongoing	FP.8 FP.10 FP.7
7.3.14	Follow radiological protection advice generally accepted at the time of use for the assessment of dose and risk (e.g. dosimetric data and the applicable risk coefficient). Uncertainties in these areas are common to all radiological assessments and are normally left implicit. There is, therefore, no special reason to include them explicitly in assessments supporting the environmental safety case for a disposal system.	paras. 416 - 430	Addressed/ Ongoing	FP.8
7.3.15	Make clear which uncertainties have been quantified and applied to parameter values used in quantitative environmental safety assessments, and the methods used for carrying out the calculations.	Section 7.7.3	Addressed/ Ongoing	FP.8
7.3.16	Show that any simplifications adopted in the environmental safety assessments either have an insignificant effect on the outcome of the assessments, or have a conservative effect (i.e. do not lead to impacts being underestimated).	Section 7.7.3	Addressed/ Ongoing	FP.8

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
7.3.17	If unquantifiable uncertainties are important to the ESC, they may be treated by a series of risk assessments, in each case making deterministic assumptions and exploring the effects of varying these assumptions.	Section 7.2.3 paras. 468 – 505	Addressed/ Ongoing	FP.8
7.3.18	In some circumstances, where few or no relevant data can be gathered, a 'stylised' approach to assessment may be adopted, in which arbitrary assumptions are made that are plausible and internally consistent but tend to err on the side of conservatism. Use of a stylised approach should not distort the modelling of the rest of the system such that important properties of other parts of the system are obscured in the overall model.	Section 7.2.3	Addressed/ Ongoing	FP.8
7.3.20	The environmental safety case will need to be updated as uncertainties related to the design, construction, operation and closure of a disposal facility are resolved as the programme develops.	Section 12.3.2	Addressed/ Ongoing	FP.14
7.3.21	Provide details of the models and methodologies used in the environmental safety assessment including any assumptions, as well as the results.	Sections 7.1, 7.6 and 7.7.3	Addressed/ Ongoing	FP.8
7.3.22(a)	Each specific set of modelling studies needs to have specific defined and documented objectives: - modelling objectives should take account of the decisions that the results are intended to support; - the selected approach should be driven mainly by the modelling objectives, and not by the availability of models or software or by considering what models or software were used previously (unless there is an overriding need for consistency); - modelling objectives should be defined in terms of what can be accomplished with the available data. Complex models should not be developed if there is not enough data to support them; - the objectives should be reviewed throughout the modelling process.	Section 7.5	Addressed/ Ongoing	FP.8
7.3.22(b)	In cases where there are likely to be extensive modelling studies, discuss the modelling objectives at an early stage with the relevant environment agency.	Section 12.2	Addressed/ Ongoing	FP.14

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
7.3.23	Carry out a systematic programme of work to build confidence in modelling. This will include interpreting raw data and developing and testing conceptual, mathematical and computational models. The measures adopted in a confidence-building programme should include: - systematic approaches to model building and consideration of alternative models; - iteration between model building, quantitative assessments and data collection; - good communication between modellers (including those developing and using models), suppliers of data (including those planning research or data collection and those actually making observations) and those using modelling results; - continuing peer review of model development; - rigorous quality assurance of all modelling activities and associated data handling, including controls over changes to models and data and a detailed audit trail.	Section 9.3	Addressed/ Ongoing	FP.8 FP.10
7.3.24	Models and associated parameter values should, to the extent possible at the time of the assessment, be site-specific. The use of generic or default data instead of site-specific data should be supported by considering the effect that this has on the ESC.	Sections 7.3 and 7.5	Addressed/ Ongoing	FP.8
7.3.25	Show that the environmental safety case is not unduly sensitive to alternative interpretations or conceptual models.	Section 7.7.3	Addressed/ Ongoing	FP.8
7.3.26	Provide the basis for the judgements to end the programme of building confidence in the modelling, area by area.	Sections 7.13 and 9.3	Addressed/ Ongoing	FP.8 FP.10
7.3.27	Show that computational models have been used in an appropriate manner, giving the ranges of values for parameters outside which the results from a model cannot be relied on together with appropriate evidence.	Section 7.6	Addressed/ Ongoing	FP.8
7.3.28	Quantitative modelling projections should not be made for times so far into the future that uncertainties make the modelling results lose any meaning.	Section 7.4	Addressed/ Ongoing	FP.8
7.3.29	As far as possible, use standard approaches to establish the environmental safety case, thus relying on appropriate expert judgement in gathering and interpreting evidence and applying it to construct and use the qualitative and quantitative models.	Section 9.3 para. 724	Addressed/ Ongoing	FP.10 FP.8

Requirement ID	Requirement Text	Where Addressed in ESC	Status	Forward Programme
7.3.30	Where expert judgement that is not held in common is used to complement or interpret evidence or to compensate for data gaps, to an extent proportionate to the significance of the judgements to the environmental safety case: - explain the choice of experts and method of elicitation; - document explicitly expert judgements that have been made and the reasons given by experts to support their judgements; - take and document reasonable steps to identify and eliminate or minimise any biases resulting from the use of expert judgement and/or the elicitation methods adopted.	Section 7.2.3	Addressed/ Ongoing	FP.8 FP.10
7.3.31	Consider the issue of a criticality event, although a simple analysis should be sufficient to demonstrate that such an event will not occur.	Sections 4.3.5 and 7.11	Addressed/ Ongoing	FP.3
7.3.32	Take into account the potential for climate change. There is considerable uncertainty regarding the rate, amount and even the direction of possible climate change over different timescales, so consider a range of possibilities. The potential consequences of climate change include changes in rainfall patterns (which can affect watercourses and aquifers), changes in sea level, increased rates of erosion including coastal erosion, glacial cycling and glaciotectonic movements.	Section 7.2.3 para. 413 Section 7.7	Addressed/ Ongoing	FP.8
7.3.33	Consider human intrusion as part of the environmental safety case - because of the associated uncertainty, this is likely to involve using stylised calculations.	paras. 468 – 474 paras. 383 – 389 Figure 7.16	Addressed/ Ongoing	FP.8
7.3.34	Demonstrate in the environmental safety case that optimisation considerations have been applied in all relevant decisions and at all relevant steps. Relevant steps include the choice of waste acceptance criteria, how the selected site is used and the design, construction, operation, closure and post-closure management of the disposal facility.	Section 5.5 para. 750	Addressed/ Ongoing	FP.6