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The Safety and Regulatory Challenges Associated with the Geological Disposal of the UK's Higher Activity Radioactive Waste in England and Wales

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Declaration of Originality

I hereby declare that this thesis and the work reported herein was composed by and originated entirely from me. Information derived from the published and unpublished work of others has been acknowledged in the text and references are given in the list of sources.

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Ashley Ian Marsh (2022)

Abstract

The UK's higher activity waste (HAW) is set to be disposed of in a geological disposal facility (GDF). International consensus is that a GDF provides the most comprehensive means of isolating and containing HAW and its harmful radionuclides, with nations at different stages in their implementation of geological disposal. The maturity of some nations' disposal programmes (e.g. Finland, Sweden) ensures a regulatory framework for their GDF is well established. The UK is currently engaged in a GDF site selection process, as such it is necessary that the regulatory framework for the geological disposal of its radioactive waste be fully established to meet the unique challenges posed by this first-of-a-kind facility for the UK. The reduced hazard potential and unique features of the GDF may mean the existing framework applied to UK nuclear installations does not proportionately meet the requirements for maintaining worker and public safety and the protection of the environment. The purpose of the work presented in this thesis was to investigate the safety and regulatory challenges associated with the geological disposal of UK HAW. This began by building an understanding of the fundamentals of radioactive waste and geological disposal in the UK and the risks associated with geological disposal. Having investigated the performance of proposed engineered barrier materials for the GDF, a simplified, 1-dimensional risk assessment model was developed for the disposal of spent nuclear fuel (SNF) in a hypothetical geological setting. The model was verified against data provided by Radioactive Waste Management Ltd (RWM Ltd), the UK's GDF delivery body, and utilised to conduct sensitivity studies, for the purpose of identify factors which could significantly impact on the radiological risk to the public due to the disposal of Spent Nuclear Fuel. Where significant, it was considered whether this might impact on the nature of the regulatory oversight required. The framework applied to nuclear installations in the regulation of nuclear safety, security, environmental protection and safeguards was mapped and analysed for its applicability to GDF-specific challenges. International experience in the regulation of GDFs was drawn upon in order to identify common features. Stakeholder opinion, including members of industry, regulators, waste producers and local interest groups, was also sought, in order to highlight their views on the applicability of the current system of nuclear site licensing to a GDF. This work culminated with a proposal for a regulatory framework, which aims to proportionately address the unique challenges associated with geological disposal.

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Convention of 31 January 1963 Supplementary to the Paris Convention of 29 July 1960

Treaty on the Non-Proliferation of Nuclear Weapons 1968

Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management 1997

Protocol to Amend the Convention on Third Party Liability in the Field of Nuclear Energy of 29 July 1960, As Amended by the Additional Protocol of 28 January 1964 and by the Protocol of 16 November 1982 (2004)

Protocol Additional to the Agreement between the United Kingdom of Great Britain and Northern Ireland and the International Atomic Energy Agency for the Application of Safeguards in the United Kingdom of Great Britain and Northern Ireland in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons 2021

European

Council Directive 2011/70/EURATOM of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste (2011)

Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment (L26/1) (2011)

Domestic (Primary)

Energy Act 1946

Basic Law for the Federal Republic of Germany 1949 (Germany)

Atomic Energy Act of 1954 (USA)

Atomic Energy Basic Law 1955 (Japan)

Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors 1957 (Japan)

Act on Prevention of Radiation Hazards due to Radioisotopes, etc. 1957 (Japan)

Act on the Peaceful Utilisation of Atomic Energy and the Protection against its Hazards 1959 (Germany)

Nuclear Installations Act 1965

Act 68-943 of 30th October 1968 on civil liability in the nuclear energy field (1968, France)

Nuclear Liability Act 1972 (Finland)

Energy Reorganization Act of 1974 (USA)

Health and Safety at Work etc. Act 1974

Department of Energy Organization Act 1977 (USA)

Nuclear Waste Policy Act of 1982 (USA)

Federal Act on the Protection of the Environment 1983 (Switzerland)

Act on Nuclear Activities 1984 (Sweden)

Nuclear Energy Act 1987 (Finland)

Act No 91-1381 of 30 December 1991 on research on radioactive waste management (1991, France)

Radiological Protection Act of 22 March 1991 (Switzerland)

Energy Policy Act of 1992 (USA)

Radioactive Substances Act 1993

Environmental Code (1998, Sweden)

Act on Special Measures Concerning Nuclear Emergency Preparedness 1999 (Japan)

Nuclear Safeguards Act 2000

Anti-terrorism, Crime and Security Act 2001

Nuclear Energy Act 2003 (Switzerland)

Energy Act 2004

Act 2006-686 on transparency and security in the nuclear field 2006 (France)

Programme Act 2006-739 of 28th June 2006 on the sustainable management of radioactive materials and waste (2006, France)

Decree No. 2007-830 of May 11, 2007 relating to the nomenclature of basic nuclear installations (2007, France)

Swiss Federal Nuclear Safety Inspectorate Act 2007 (Switzerland)

Swedish Radiation Safety Authority Regulatory Code (2008, Sweden)

Act for the Establishment of the Nuclear Regulation Authority 2012 (Japan)

Energy Act 2013

Law on the establishment of a Federal Office for the Safety of Nuclear Waste Management 2013 (Germany)

Act on the Search and Selection of a Site for a Repository for Heat-Generating Radioactive Waste and for the Amendment of Other Laws 2017 (Germany)

Act on Radiation Protection 2018 (Sweden)

Nuclear Safeguards Act 2018

Radiation Protection Act 2018 (Finland)

Act on the Protection against the Harmful Effect of Ionising Radiation 2018 (Germany) Public Health Code (2019, France)

Domestic (secondary)

Ordinance on the Procedure for Licensing of Installations under § 7 of the Atomic Energy Act 1977 (Germany)

Nuclear Industries Security Regulations 2003

Nuclear Energy Ordinance of 10 December 2004 (Switzerland)

Nuclear Safeguards (Notifications) Regulations 2004

Decree 2007-1557 relative to basic nuclear installations and oversight of the transport of radioactive substances from the nuclear safety aspect 2007 (France)

Ordinance on the Procedure for Licensing of Installations under § 7 of the Atomic Energy Act 1977 (Germany)

Ordinance with Instructions for the Swedish Radiation Safety Authority 2008 (Sweden)

Regulations and general advice on the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste 2008 (Sweden)

Regulations concerning safety in connection with the disposal of nuclear material and nuclear waste (2008, Sweden)

Ordinance on the Shipment of Radioactive Waste or Spent Fuel 2009 (Germany)

Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste 2010 (Germany)

Natural Resources Body for Wales (Establishment) Order 2012

Order of 7 February 2012 setting the general rules relative to basic nuclear installations (2012, France)

Environmental Permitting (England and Wales) Regulations 2016

The Nuclear Installations (Liability for Damage) Order 2016

Infrastructure Planning (Environmental Impact Assessment) Regulations 2017

Ionising Radiations Regulations 2017

Radiological Protection Ordinance of 26 April 2017 (Switzerland)

Town and Country Planning (Environmental Impact Assessment) (Wales) Regulations 2017

Nuclear Installations (Prescribed Sites and Transport) Regulations 2018

Ordinance on Protection against the Harmful Effects of Ionizing Radiation 2018 (Germany)

Radiation and Nuclear Safety Authority Regulations on the Safety of Disposal of Nuclear Waste 2018 (Finland)

Nuclear Safeguards (EU Exit) Regulations 2019

Radiation (Emergency Preparedness and Public Information) Regulations 2019

List of Abbreviations

ACSA	Anti-terrorism, Crime and Security Act 2001
AEA54	Atomic Energy Act 1954 (US)
AEC	Atomic Energy Commission (US)
AGR	Advanced Gas-Cooled Reactor
ALARA	As Low as Reasonably Achievable
ALARP	As Low as Reasonably Practicable
AM05	Goldsim model derived by author
ANA84	Act on Nuclear Activities (1984) (Sweden)
API	Additional Protocol Information
ARP18	Act on Radiation Protection (2018) (Sweden)
ASN	The Autorité de sûreté nucléaire (Nuclear Safety Authority, France)
ATCSA	Anti-terrorism, Crime and Security Act 2001
AVH	Atelier de Vitrification La Hague process
BAMBUS II	Backfill and Material Behaviour in Underground Salt Repositories project
BAT	Best Available Techniques
BEIS	Department for Business Energy and Industrial Strategy
BfE	Federal Office for the Safety of Nuclear Waste Management (Germany)
BFS	Blast Furnace Slag
BfS	Federal Office for Radiation Protection (Germany)
BMUB	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (Germany)
BNI	Basic Nuclear Installation

C-S-H	Calcium-silicate-hydrate
CDF	Cumulative Distribution Function
CEC	Cation Exchange Capacity
CFR	US Code of Federal Regulations
CNSS	ONR Civil Nuclear Security and Safeguards division
CoRWM	Committee on Radioactive Waste Management
CSP	The Public Health Code (France)
DCO	Development Consent Order
DETEC	Federal Department of the Environment, Transport, Energy and Communications (Switzerland)
DI	Derived Inventory
DOE	US Department of Energy
DP	Derived Powers
EBS	Engineered Barrier System
EC	Environment Code
EIA	nNvironmental Impact Assessment
EIM&C	Enhanced Implementation, Monitoring and Control
EIMT	Examination, Inspection, Maintenance and Testing
EIS	Environmental Impact Statement
ENSI	The Swiss Federal Nuclear Safety Inspectorate
ENSIG	Swiss Federal Nuclear Safety Inspectorate Act
EP	Environmental Permit
EPA	Environmental Protection Agency
EPA83	Federal Act on the Protection of the Environmental (Switzerland)
EPA92	Energy Policy Act 1992 (US)
EPR	Environmental Permitting (England and Wales) Regulations 2016
ESC	Environmental Safety Case
F-PSAR	First/Preliminary Safety Analysis Report

FANC	Federal Agency for Nuclear Control (Belgium)
FDA00	Designated Radioactive Waste Final Disposal Act 2000 (Japan)
FOPH	Federal Office of Public Health (Switzerland)
FP	Fission Product
FSC	Facility Safety Case
FSyPs	Fundamental Security Principles
GDF/DGR	Geological Disposal Facility/Deep Geological Repository
GI	Geological Investigation
gPCSA	Generic Post Closure Safety Assessment
GRA	Guidance on Requirements for Authorisation
GRR	Guidance on Requirements for Release
GSR	IAEA General Safety Requirements
HAL	Highly Active Liquor
HAW	Higher Activity Waste
HHGW	High Heat Generating Waste
HLW	High-Level Waste
HSE	Health and Safety Executive
HSR	High Strength Rock
HSWA	Health and Safety at Work Act 1974
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IESC	Initial Environmental Safety Case
ILW	Intermediate-Level Waste
IRF	Instant Release Fraction
IRR	Ionising Radiations Regulations 2017
ISE	Initial Site Evaluation
ISO	International Organisation for Standardization

LC '72	London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter
LCs	Licence Conditions
LHGW	Low Heat Generating Waste
LIs	Licence Instruments
LLW	Low-Level Waste
LLWR	Low Level Waste Repository Ltd
LoC	Letter of Compliance
LOT	Long Term Test of Buffer Material
LSSR	Lower Strength Sedimentary Rock
MBGWS	Miscellaneous Beta Gamma Waste Store
MEAE	Ministry of Economic Affairs and Employment (Finland)
MEP	Magnox Encapsulation Plant
METI	Ministry of Economy, Trade and Industry (Japan)
MoD	Ministry of Defence
MoU	Memorandum of Understanding
MW	Magnox Waste Simulant
NAGRA	The National Cooperative for the Disposal of Radioactive Waste (Switzerland)
NAIR	National Arrangements for Incidents Involving Radioactivity
NDA	Nuclear Decommissioning Authority
NEA03	Nuclear Energy Act 2003 (Switzerland)
NEA87	Nuclear Energy Act 1987 (Finland)
NEPC	Nuclear Energy Preparedness Commission (Japan)
NI	Nuclear Installation
NIA65	Nuclear Installations Act 1965
NIEA	Northern Ireland Environment Agency
NIR71	Nuclear Installations Regulations 1971
NIREX	United Kingdom Nirex Ltd

NISR	Nuclear Industries Regulations 2003
NPS	National Policy Statement
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRA	The Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission (US)
NRVB	NIREX Reference Vault Backfill
NRW	Natural Resources Wales
NSA	Nuclear Safeguards Act 2000
NSA00	Nuclear Safeguards Act 2000
NSA18	Nuclear Safeguards Act 2018
NSC	Nuclear Safety Commission (Japan)
NSC	Nuclear Safety Committee
NSC	Swiss Federal Nuclear Safety Commission
NSIP	Nationally Significant Infrastructure Project
NSL	Nuclear Site Licence
NSR	Nuclear Safeguards (Notifications) Regulations 2004
NSR19	Nuclear Safeguards (EU Exit) Regulations 2019 (NSR19)
NUMO	Nuclear Waste Management Organisation (Japan)
NWMO	Nuclear Waste Management Organisation (Canada)
NWS	Nuclear Waste Services
OECD	Organisation for Economic Co-operation and Development
ONR	Office for Nuclear Regulation
OPC	Ordinary Portland Cement
OSPAR	Convention for the Protection of the North East Atlantic
PA08	Planning Act 2008
PCmSR	Pre-Commissioning Safety Report
PCSR	Pre-Construction Safety Report
PDmSR	Pre-Decommissioning Safety Report

PEG	Potentially Exposed Group
PESE	Preliminary Environmental Safety Evaluation
PFA	Pulverised Fuel Ash
PINS	Planning Inspectorate
POCO	Post-operational clean-out
pOECS	Post-Operational Environmental Safety Case
POESC	Pre-Operational Environmental Safety Case
POSR	Pre-Operational Safety Report
PP	Primary Powers
PRP	Prototype Repository Projects
PRTI	Potential Rock Types of Interst
PSR	Preliminary Safety Report
PWR	Pressurised Waster Reactor
QNL	Quarterly Notification Levels
REA	Relevant Environment Agency
REPOPERM	Residual Porosity and Permeability
REPPIR	Radiation (Emergency Preparedness and Public Information) Regulations (2019)
RGL	Risk Guidance Level
RHPA	ct on Prevention of Radiation Hazards due to Radioisotopes, etc. (Japan)
RPA18	Radiation Protection Act 2018 (Finland)
RPA91	Radiological Protection Act 1991 (Switzerland)
RPI	Radiation Protection Inspectorate (France)
RRA57	Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (Japan)
RSA	Radioactive Substances Act 1993
RSR	Radioactive Substances Regulation
RWA	Radioactive Waste Adviser
RWM	Radioactive Waste Management Ltd

SAP	Safety Assessment Principles
SAR	Safety Analysis Report
SCC	Stress Corrosion Cracking
SEPA	Scottish Environment Protection Agency
SFAIRP	So Far As Is Reasonably Practicable
SFOE	Federal Office of Energy (Switzerland)
SJR	Site Justification Report
SKB	The Swedish Nuclear Fuel and Waste Management Company
SMP	Safety Management Prospectus
SNF	Spent Nuclear Fuel
SNI	Sensitive Nuclear Information
SRLs	WENRA Safety Reference Levels
SSM	The Swedish Radiation Safety Authority
SSR	IAEA Specific Safety Requirements
STUK	The Radiation and Nuclear Safety Authority (Finland)
SWESC	Site Wide Environmental Safety Case
SyAPs	ONR Security Assessment Principles
TAG	ONR Technical Assessment Guide
TEA13	Energy Act 2013
TEC98	The Environmental Code (1998) (Sweden)
TSM	Total System Model
TSS	Transport Security Statement
UCS	Unconfined/Uniaxial Compressive Strength
UESC	Updated Environmental Safety Case
UKRWI	United Kingdom Radioactive Waste Inventory
UVPG	Environmental Impact Assessment Act (Germany)
VLLW	Very Low-Level Waste
VOA	Voluntary Offer Agreement

VPS	Vitrification Product Store
VwVfG	Administrative Procedures Act
WAC	Waste Acceptance Criteria
WAL	Weekly Advisory Levels
WENRA	Western European Nuclear Regulators Association
WEP	Waste Encapsulation Plant
WIPP	Waste Isolation Pilot Plant
WPS	Waste Package Specification
WVP	Waste Vitrification Products

Chapter 1

Introduction

1.1 Project Motivation & Background

The UK has utilised nuclear energy for civil and military purposes since the 1950s, and its net-zero strategy acknowledges nuclear energy will play a role in the decarbonisation of the UK's power system by 2035 [1], [2]. As a result, a significant inventory of radioactive waste, which is defined as radioactive material with no further use and which is contaminated by or incorporates radioactivity above the levels defined in legislation, is present across nuclear licensed sites and non-licensed sites in the UK [3]–[5]. Based on assumptions made in the 2019 Radioactive Waste Inventory, which is made up of materials originating from reactor operations, decommissioning activities, defuelling and reactor shut downs across UK nuclear sites, it is anticipated that future arisings of radioactive waste will top 4.4 million m^3, taking the total inventory to $\sim$ 4.6 million m^3 by 2135 [6]. A large proportion of this waste is classed as low-level (LLW) or very low-level (VLLW) waste, which may be disposed of via near-surface radioactive waste disposal or conventional landfill facilities. UK policy dictates the small proportion of LLW unsuitable for disposal by these methods will be permanently disposed of in a geological disposal facility (GDF), along with so-called "Higher Activity Wastes" (HAW) [7]. GDF's have been proposed for the disposal of HAW or spent nuclear fuel (SNF) in a number of nations,

including, Sweden, France, Switzerland, Canada and the UAE. The Waste Isolation Pilot Plant (WIPP) in New Mexico, USA, built for the disposal of transuranic military wastes, has been operational for over 20 years, whilst the Onkalo Deep Geological Repository (DGR) in Finland is the most developed of those currently proposed for the disposal of civil waste, with excavation of the first disposal tunnels commencing in May 2021 [8].

The delivery of a GDF will be vital not only for the management of legacy radioactive waste but also to the long-term future of the UK's nuclear industry. As of December 2018, Radioactive Waste Management Ltd (RWM) has recommenced the UK's site selection process for the UK's GDF [9]–[11]. In January 2022, RWM officially formed part of a new combined legal entity, along with Low Level Waste Repository Ltd (LLWR), known as Nuclear Waste Services (NWS).

A GDF will be a unique nuclear installation for the UK, and bring its own distinct challenges relevant to human health, environmental protection, security and non-proliferation. The Government has indicated that a GDF will be licensed under the Nuclear Installations Act, and it is recognised that further work is needed on the application of the UK nuclear site licensing regime to a GDF [12], [13]. The primary motivation for this project is therefore to utilise the available information and understanding of geological disposal, and the associated risks to the public and the environment, to address the safety and regulatory challenges posed by geological disposal in the UK, and develop an appropriate regulatory framework which can be applied to the GDF.

1.2 Research Aims & Objectives

The aim of this project was to explore the safety and regulation of a geological disposal facility for the UK's higher activity radioactive wastes and draw some conclusions on the appropriateness and efficacy of the existing regulatory framework.

1.2.1 Project Scope

The project addressed the characteristics and categorisation of radioactive waste, waste disposal methodologies and engineered barriers, and also looked at the three principal geological settings proposed as suitable hosts for a GDF in England and Wales namely: fractured high strength rocks, lower strength sedimentary rocks/clays and evaporites.

The risk to future generations was investigated, whilst work also addressed the role of land use planning, environmental permitting, and nuclear site licensing on the regulation of nuclear installations, and the impact of Government policy. International approaches and experience were used to compare the existing approach to the regulation of nuclear installations in England and Wales to the regulation of GDFs/DGRs in those countries.

The project examined the regulatory challenges unique to geological disposal and evaluated the options for a regulatory framework to effectively control the design, construction, commissioning, operation, and closure of a GDF in England or Wales.

Therefore the purpose of the work reported in this thesis was to:

1. Investigate the issues associated with the fundamentals of geological disposal of HAW as defined in the UK, the candidate geological environments for the GDF and the type of materials which may be utilised in a multi-barrier, engineered barrier system.

2. Analyse the radiological risk associated with the disposal of spent nuclear fuel in a generic clay geological setting, and the impact of assumed sensitivities on the risk posed to members of the public, from the time of deposition up until 1 million years.

3. Propose how a GDF could be regulated in the UK, based on national and international practices.

1.3 Thesis Structure

Chapter 2 of this thesis outlines the fundamental principles of radioactive waste and geological disposal in the United Kingdom, including waste classification and conditioning, the waste inventory and generic geological settings for deep geological disposal. Chapter 3 introduces the concept of the "engineered barrier system" which will be employed as part of the GDF; candidate materials identified as potentially suitable for the UK's GDF are discussed.

In Chapter 4, the important role of each distinct engineered barrier is outlined, and the performance characteristics of a number of candidate materials described to provide an indication as to their expected lifetime in the GDF.

Chapter 5 outlines the development and implementation of an original, 1-dimensional risk assessment model for the simulation of radionuclide release from spent nuclear fuel disposed of in a hypothetical clay environment. The annual radiological risk posed to potentially exposed groups was identified and sensitivity studies conducted to identify which factors of GDF design, construction, or operation, may contribute significantly to the risk posed to future generations.

Chapter 6 outlines the UK's international obligations with respect to radioactive waste management, and summarises how the regulation of geological disposal is being addressed in 7 other nuclear nations: Finland, Sweden, Germany, France, Switzerland, USA and Japan. Chapter 7 maps out the existing legislative and regulatory framework for nuclear installations in England and Wales in areas of nuclear safety, security, environmental protection, safeguards and land-use planning, from which permissioning regimes have been established.

Chapter 8 provides an analysis of the regulatory framework outlined in Chapter 7 and its suitability for geological disposal. This includes identification of areas in the regulatory framework which require amendment in order to meet the unique requirements of geological disposal. Stakeholder opinion from industry, regulator, and local/community interest groups was sought on matters relevant to the nuclear site licensing process in the UK. The focus of Chapter 9 is the proposal of a proportionate regulatory framework for the UK's GDF. This outlines a

number of possible amendments to legislation, regulations and guidance which might be useful or required in order to ensure that the GDF is regulated proportionately under nuclear site licensing, environmental permitting and security and safeguards regimes.

Finally, Chapter 10 brings together the findings of the PhD project, highlighting the major findings and drawing attention to potential areas where future work would be recommended.

Chapter 2

Geological Disposal of Higher Activity Waste in England and Wales

2.1 Introduction

The Nuclear Decommissioning Authority's (NDA) 2019 Radioactive Waste Inventory reported a total volume of 133,000 m^3 of radioactive waste, as of April 1st 2019 , with projections indicating the UK's radioactive waste inventory could reach 4,560,000 m^3 by 2135 when accounting for key events such as the decommissioning of the UK's Magnox and advanced gas-cooled (AGR) reactors and the ceasing of spent fuel reprocessing [5], [6]. Nuclear power is still regarded as an important contributor to the UK's future energy mix and to meeting the government's 2050 net-zero carbon emissions targets, and evidently its use will result in the generation of further radioactive waste which requires considered and proportionate management [14].

The UK's classification system for radioactive waste is dictated by two main factors: radioactivity levels and heat generation [15]. There are currently four main categories used to group the UK's radioactive waste (described in section 2.2.1): high- (HLW), intermediate- (ILW), low- (LLW), and very low- (VLLW) level radioactive wastes. Materials such as spent nuclear fuel, which

are not yet declared waste, may be in the future. The quantities and composition of the UK's radioactive wastes are discussed in section 2.2.2.

International consensus and UK policy agree that deep geological disposal is the most effective solution for the long-term management of higher activity radioactive waste [7], [16]–[18]. The UK is currently embarking on a fifth decade of research and community engagement, to identify a site suitable for a geological disposal facility (GDF) [19]. The GDF will be used for the disposal of so-called "higher activity wastes" (HAW), which comprise heat generating HLW, ILW and some long lived LLW. These wastes contain the majority of the UK inventory's radioactivity, ergo radiological risk to the public and environment if not stored and disposed of adequately. The GDF will be located in one of three generic geological settings available in the UK, i.e. high strength rock (HSR), lower strength sedimentary rock (LSSR) or evaporitic (salt) environments, these are discussed in section 2.4.

The GDF will be a facility unlike any other currently in the UK, which will present unique regulatory challenges. The facility will be underground in a 3-dimensional space, at depths of 200-1000 m, above which there could be residential, industrial, and commercial properties and privately owned land. The regulatory framework will need to accommodate the GDFs unique characteristics and be robust enough to provide sufficient control over the facility's lifecycle from design through construction, commissioning, operation and closure. The regulatory framework will also need to reflect the risks posed by the radioactive material in a GDF to ensure that it provides a proportionate level of regulatory oversight over issues of safety, security, environmental protection and safeguards/non-proliferation.

This chapter initially sets out the UK's waste classification system, defining the higher activity waste that will ultimately reside within the UK's GDF. It includes the radioactive wasteform conditioning methodologies (2.2.1.3), inherent characteristics of the waste for disposal (2.2.1.4) and the scale of the UK's waste inventory (2.2.2). Having established what is meant by radioactive waste in a UK context, concepts of waste disposal, including deep geological disposal are outlined (2.3), including the UK's progress to date in implementing geological disposal

(2.3.2.2). The geological settings for a UK GDF, their availability and the properties which make them suitable for disposal are also outlined (2.4). The implications of this information on the regulation of geological disposal are summarised (2.5), including where it opens up areas for further research (2.6).

2.2 Radioactive Waste in the UK

The radioactive waste inventory for the UK is complex, made up of fission products, actinides and other wastes arising from the reprocessing of spent nuclear fuel (SNF), activated and contaminated materials from nuclear facility operations, decommissioning and site clean-up. What the UK regards as radioactive waste for disposal, and how it divides its total inventory differs from some international regimes, which for example regard SNF as a HLW under their own systems for classification [20]. The UK's approach to waste classification and definitions of the categories of waste in its inventory are outlined in 2.2.1.

2.2.1 Waste Classification

As the UK's radioactive waste inventory is sorted by its radioactivity and heat generation, this has allowed all materials considered waste to be categorised, and an appropriate route for disposal (where disposal is the optimal choice) identified [15].

2.2.1.1 Waste Destined for Geological Disposal

The UK's GDF is intended to be a permanent disposal solution for all HAWs. HAW is defined as any radioactive material that belongs to the classes of high- (HLW) and intermediate- (ILW) level wastes, as well as a small quantity of low-level waste (LLW), which isn't suitable for disposal at existing facilities [21].

High-Level Waste

High level waste (HLW) comprises waste that generates heat due to its high level of radioactivity [22], [23]. It contains a large concentration of short and long lived radionuclides, at levels significantly above those in intermediate-level waste (ILW), such that it requires a greater level of isolation and containment from the accessible environment [22]. Typically the activity levels of HLW corresponds to values in the region of 10^4 TBq/m^3, after a significant period of cooling [24]. The majority of the UK's HLW inventory is derived from the reprocessing of SNF, in which uranium and plutonium are extracted and recovered for use in fuel manufacture. The last of the UK's reprocessing activities will cease in July 2022 [25].

HLW can comprise small quantities of scrap materials arising from reprocessing facilities, consisting of ceramic and metal from plant items that are treated as HLW due to contamination by vitrified HLW glass. Typically however HLW arises as a so-called "highly active liquor" (HAL), resulting from the dissolving of spent nuclear fuel in concentrated nitric acid [26]. This liquor contains waste fission products (FPs), with high levels of radioactivity, and exhibits significant heat output. HAL is vitrified (see 2.2.1.3) to form a stable, solid HLW wasteform which immobilises over 30 elements, including FPs and actinides, along with process and fuel additives, corrosion products and elements originating from residual cladding materials, which are combined with base glass components [6], [26], [27].

Intermediate-Level Waste

International safety standards define intermediate-level waste (ILW) as waste that exhibits significant levels of long lived radionuclides such that containment and isolation far beyond the capabilities of a near surface disposal, are required [22]. ILW requires more shielding than waste that can be disposed of at or near the surface, but unlike HLW exhibits little-to-no thermal output [20]. In the UK wastes are classed as ILW if they exceed the limit of radioactivity set for Low-Level Waste (LLW), which is 4 GBq.T^{-1} for alpha emitting materials and 10-12 GBq.T^{-1} for beta and gamma emission, or a decay heat < 2 kW.m^{-3} (a threshold which defines HLW)

[7], [20], [28].

ILW comprises an array of materials, including graphite, plutonium contaminated materials, fuel cladding, contaminated metals and "wet ILW" (e.g. sludge, flocculants, ion exchange resins)[29]. Graphite, which is utilised as a moderator in Magnox and AGR reactors, corresponds to the single largest contributor (∼27% by volume) to the ILW inventory [30]. Most of the ILW which has arisen to date currently resides in interim storage in an untreated or partially treated form, awaiting further treatment prior to conditioning for disposal (described in 2.2.1.3).

Low-Level Waste

Low-level waste (LLW) refers to radioactive waste which falls below the activity thresholds for ILW, which may be safely disposed of by near-surface disposal [23]. The majority of LLW arisings are made up of items that have been contaminated with low levels of radioactivity, including personal protective equipment, plant items, liquid effluents, cementitious materials, plastics, scrap metals, soil and steel items [6]. A small proportion of UK LLW is not suitable for disposal for near-surface disposal and will be disposed of with other HAW, due to factors which may include failure to meet waste acceptance criteria (WAC), exhibiting radioactivity close to threshold levels or difficulties in its separation from ILW [31].

2.2.1.2 Other Materials Requiring Disposal

The UK Radioactive Waste Inventory (UKRWI) also takes account of wastes suitable for disposal at near-surface or conventional landfill sites (i.e. very low-level waste) and quantities of materials for which no permanent means of disposal currently exist (i.e. spent nuclear fuel).

Very Low-Level Waste

Radioactive waste which is classed as very low-level (VLLW) typically contains materials which are lightly contaminated by radioactive elements, and is anticipated to contribute to ~ 60 % of the total packaged volume of radioactive waste in the UK by 2125 [6]. Small quantities originate

from hospital and university facilities, and are safely disposed of with municipal, commercial, or industrial waste; larger volumes from nuclear sites are disposed of via permitted landfill. VLLW comprises mainly structural building materials and excavated soils arising from decommissioning, demolition and site clean-up operations [6].

Spent Nuclear Fuel

Spent nuclear fuel (SNF) comprises any form of irradiated nuclear fuel that is permanently removed from a reactor core [32]. Though considered as a component of the UK's future inventory requiring disposal, SNF is not currently designated as radioactive waste for disposal via geological disposal. A number of countries have adopted a once through fuel cycle and intend to dispose of SNF directly to their own GDF/DGR. The UK's current inventory of SNF is largely made up advanced gas-cooled reactor (AGR) and pressurised-water reactor (PWR) fuels, a small proportion of experimental and research fuels and legacy Magnox fuel [33].

2.2.1.3 Conditioning of HAW

Though work is ongoing to finalise a disposal route for the UK's HAW, it is necessary for waste to be conditioned, so that it can be safely stored, handled, and/or transported prior to final disposal. As reflected in the UK Radioactive Waste Inventory (UKRWI), a proportion of the UK's HLW, ILW and LLW has already been conditioned awaiting disposal [6]; techniques utilised to condition and package radioactive waste are therefore well established, and conducted in accordance with nuclear site licence requirements (pending the establishment of future WAC), and are summarised herein.

High-Level Waste Vitrification

In the UK, HLW is conditioned using the second generation "Atelier de Vitrification La Hague" (AVH) process, adopted in the early 1980s [27]. The AVH procedure is a French-developed, high throughput two-step process, which relies on sequential waste calcination and melting/pouring, as outlined in Figure 2.1.

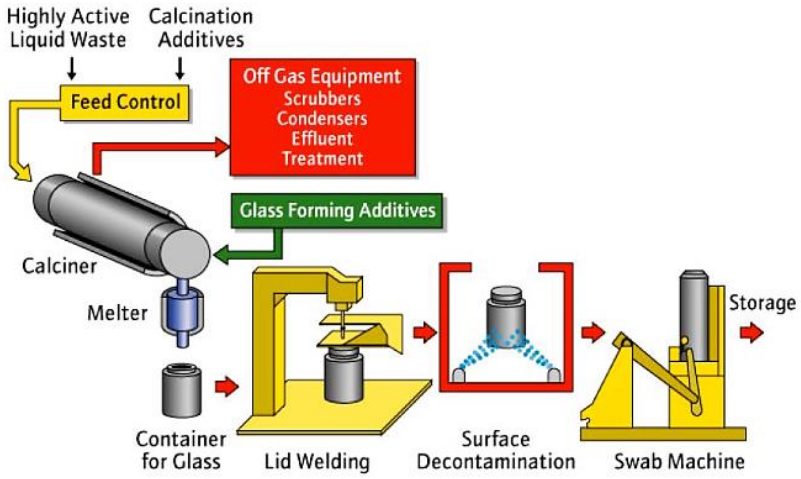


Figure 2.1: Schematic of the AVH HLW conditioning process [27].

Calcination commences when HLW liquor is fed into a stock tank with lithium nitrate and sugar solutions, which are added to ensure favourable chemical conditions for the production of a dry calcine, with minimal ruthenium volatilisation and maximal de-nitration [27], [34], [35]. This solution is passed into an electrically heated, inclined, rotary calciner, rotated at a rate of 20-30 rpm at 600-840 °C, allowing components of the liquor to evaporate and the remaining constituents to form a dry, de-nitrated "calcine" powder.

Table 2.1: The composition of glass frit utilised in UK HLW immobilisation [27]

Glass	SiO_2	B_2O_3	Na_2O	Li_2O
MW-$\frac{1}{2}$ Li	63.41	22.50	11.35	2.74

The calcine is batch fed into a metallic alloy melting vessel, to which a measured quantity of inactive MW-$\frac{1}{2}$ Li glass frit is added, the composition (weight %) of which is detailed in Table 2.1. This formulation was optimised to improve calcine reactivity in the melter by suppressing the formation of heat resistant oxides. This is heated to >1000 °C and an air sparge applied to homogenise the solution. The molten mixture is readied for pouring and fed into 169 litre, 309

stainless steel containers. After a period of cooling, lids are fusion welded, containers treated in a decontamination chamber and stored in naturally convection cooled Vitrification Product Stores (VPS).

Intermediate- and Low- Level Waste Encapsulation

The majority of the UK's ILW has been encapsulated in cement due to its favourable thermal stability, compressive strength and radiation durability. In-line or in-drum cementation is conducted across a number of facilities, including the Dounreay Cementation Plant, Sellafield Waste Encapsulation Plant (WEP) and Magnox Encapsulation Plant (MEP).

In-line cementation relies on the pre-mixture of ILW components with cementitious materials. For example raffinate resulting from the reprocessing of Dounreay Fast Reactor fuel is neutralised with sodium hydroxide before the addition of a cementitious composite in-line (comprising Ordinary Portland Cement/Pulverised Fuel Ash (OPC/PFA) in a ratio of 1:1, though previously a 9:1 Blast Furnace Slag/Ordinary Portland Cement (BFS/OPC)) blend has also been utilised. After pouring (into a stainless steel disposal container) this is cured to generate the final ILW wasteform [36], [37].

At the MEP and WEP, ILW including that produced from spent fuel reprocessing is conditioned in-drum, with both the waste and encapsulant being mixed in the final disposal container. Sheared and leached clad materials from oxide fuel reprocessing, fuel element appendages and scrap steel from remote handling operations, raffinates and slurries are all treated in this way [38]. ILW is conditioned for disposal in one of twelve standard waste package containers, including 500 litre, 316L stainless steel or concrete drums, 3 m^3 boxes and drums and 2 or 4 m boxes, with varying degrees of shielding requirements [39]. When waste is combined with a cement blend, it is mixed using either a re-usable or sacrificial paddle, to ensure the waste distribution is as even as possible before curing. Further cement capping may be utilised to minimise void space, which would then be cured again before a lid is welded into position, and the wasteform is decontaminated. The composition of cements utilised will depend on the desired flow properties.

Generally, these compositions comprise a mixture of OPC with a proportion of BFS or PFA, for a high pH environment (∼11.5), which maintains wasteform stability.

For wastes requiring a "dry" (water free) encapsulant, organic thermosetting polymers can be employed, such as bitumen (not currently employed in UK ILW conditioning), epoxy resins and vinyl-ester styrene [40], [41]. Wastes containing materials such as aluminium, magnesium and uranium, which may be react adversely to the presence of water, and ion exchange resins or radium contaminated wastes are often conditioned in this way.

2.2.1.4 Waste Characteristics

After being conditioned, wasteforms should be considered passively safe, allowing them to be stored prior to final disposal. The GDFs design and layout will be influenced by their inherent properties, such as the effects of heat dissipation or radiation on neighbouring packages and other materials utilised in the repository. It is critical therefore to understand the safety implications of the interactions between the conditioned waste packages and the GDF engineered barrier materials, and if this brings challenges to the regulation of radioactive waste disposal in the UK GDF.

High Level Waste

As described in 2.2.1.3, UK high-level waste (HLW) is conditioned to immobilise fission products and some minor actinides in borosilicate glass. Each HLW container contains approximately 150 litres of vitrified high-level waste and it is anticipated there will be in the region of 8,000 containers to be disposed of in the GDF. The inherent stability of the glass under disposal conditions, high chemical durability at elevated temperatures, the immobilisation of a large range of elements and irradiation tolerance make it a highly suitable medium for the immobilisation of HAL [42], [43].

High-level waste contains many fission products and radioactive daughters. The relatively short-lived radionuclides such as caesium-137, strontium-90 and their daughter elements

yttrium-90 and barium-137m, dominate the inventory's activity for a relatively short timescale, as in Figure 2.2, with contributions to total radioactivity in the region of 10^5-10^6 TBq.

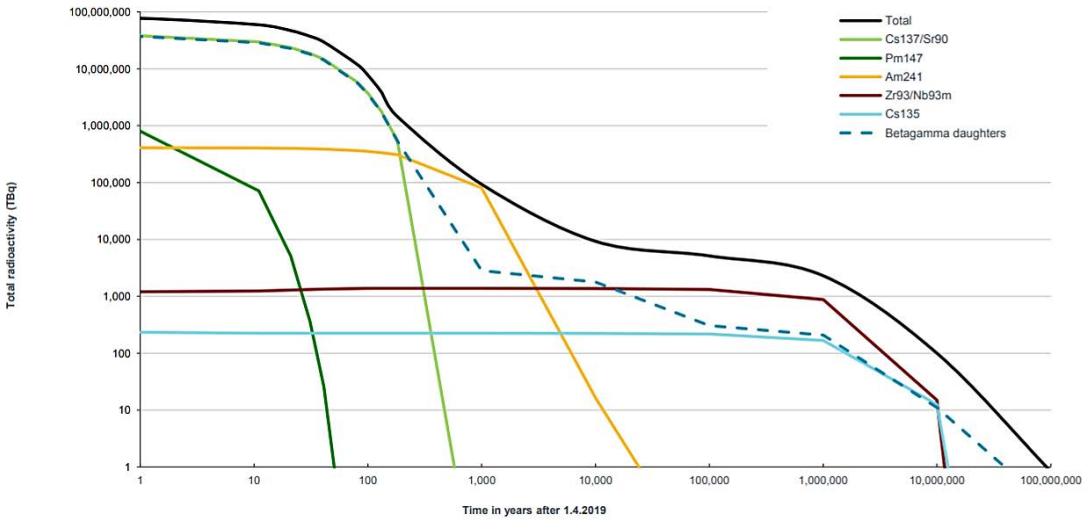


Figure 2.2: Total radioactivity of HLW inventory over time, with major contributors highlighted [6].

The contribution of caesium-137 and strontium-90 to total inventory activity quickly diminishes, on account of their characteristically short half-lives (<30 years). FPs such as zirconium-93, selenium-79, technetium-99 and iodine-129, with half-lives in the region of 2 x 10^5-1.6 x 10^7 years, are expected to dominate thereafter. It's essential that the disposal solution for HLW provides containment for tens of thousands of years, such that the decay of these important radionuclides can take significant effect. This level of activity can also have implications on the corrosivity of the surrounding environment; as such containers are designed to ensure external dose rates below (∼1-10 Gy.hr^{-1}) [41].

HLW differs from ILW in that it is defined as exhibiting decay heat >2 kw.m^{-3}. Through careful consideration of the waste loading in the vitrification process, HLW wasteforms to be disposed of in the GDF will however not exceed a radiogenic heat output of 1 kW.m^{-3} [44]. Heat output is limited to ensure transport container lid seals are maintained within a safe operating range, tolerant to accident conditions, and to prolong the neutron shielding provided by the transport container [44], [45]. It is likely that HLW wasteforms will exhibit significantly less than the

maximum heat output, in the region of 0.2-0.3 kW.m^{-3} by the time of final disposal [41]. Heat generation is important to consider due to its potential to induce wasteform, waste container, and engineered barrier damage, corrosion or degradation such as HLW de-vitrification.

It is also critical that HLW wasteforms immobilise radionuclides beyond the point at which engineered barriers fail. Wasteform glass will undergo slow dissolution in the presence of groundwater; refined estimates of the long term stability of HLW glasses and data from international programmes estimate glasses may dissolve at rates as low as 0.22 μm.yr^{-1}, resulting in total dissolution lifetimes (time required for HLW wasteform to fully dissolve and mobilise in groundwater) of 50,000-1,000,000 years [41], [46]–[48].

Intermediate Level Waste

Contaminated graphite moderator materials are a major constituent of ILW, in which a number of critical radionuclides reside, such as long-lived chlorine-36 ($t_{1/2}$=3 x 10^5 years), and the shorter-lived carbon-14 [49], [50]. Activation products are particularly prevalent in steel reactor components, including niobium-94 ($t_{1/2}$= 2 x 10^4 years) and nickel-63 ($t_{1/2}$= 100 years). Short-lived radionuclides such as nickel-63, iron-55 ($t_{1/2}$ = 2.7 years) and cobalt-60 ($t_{1/2}$-=5.27 years) with activities on the order of 10^5 TBq, are expected to dominate the first few hundred years of the ILW activity profile, as demonstrated in Figure 2.3, along with FPs such as caesium-137 and strontium-90.

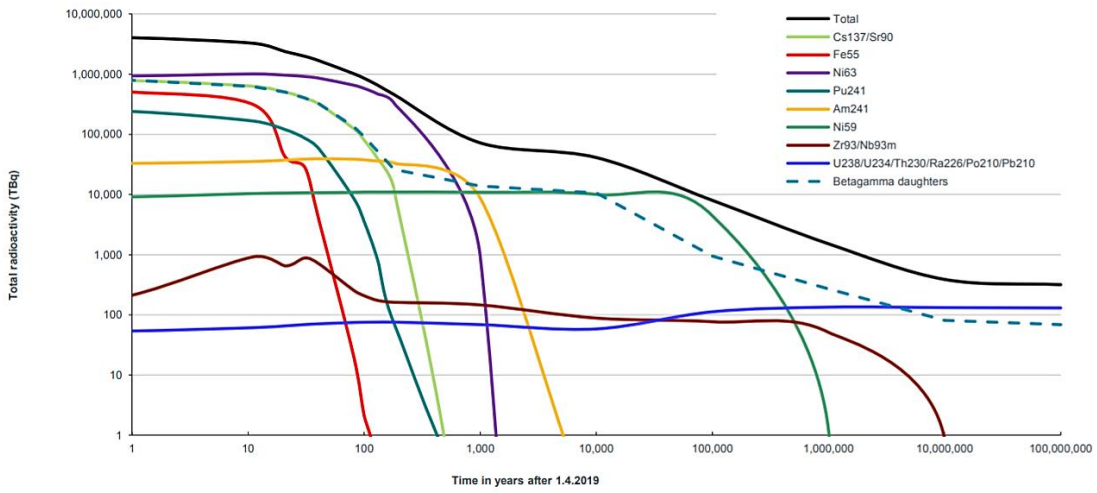


Figure 2.3: Total radioactivity of ILW inventory over time, with major contributors highlighted [6].

Long lived radionuclides, like caesium-135 ($t_{1/2}$= 2.30 x 10^6 years), niobium-92 ($t_{1/2}$= 3.5 x 10^7 years) and samarium-147 ($t_{1/2}$= 1.06 x 10^{11} years), contribute a much smaller level of total radioactivity. Beyond 10^5 years, longer-lived radionuclides such as nickel-59, the beta/gamma daughters of fission products and the presence of uranium-238 and it's radioactive daughters, are likely to dominate the total radioactivity of the UK's ILW.

2.2.2 UK Waste Inventory

Every three years the Department for Business, Energy and Industrial Strategy (BEIS) and NDA compile a record of the UK's radioactive waste and materials[6], [30], [51], [52]. In doing so they ensure the UK meets international reporting obligations, aiding the development of policy and radioactive waste management plans, whilst also making data accessible to a range of stakeholders.

The UKRWI provides an overview of UK radioactive waste management activities and quantifies the UK's radioactive waste by volume, mass and activity, as well as outlining the composition of the entire inventory, at the time of inventory and anticipated future arisings [6]. Knowledge

of the characteristics and volume of waste for disposal will inform the design and expected performance of future disposal routes, including the GDF.

As of April 1, 2019, the UK reported over 104,000 m^3 of waste that is classed as HAW [6]. Of this, 102,000 m^3 (127,000 tonnes) is a mixture of packaged and not-yet-packaged ILW and 2,150 m^3 (4,000 tonnes) of HLW at Sellafield alone. Of the 27,340 m^3 of LLW, the volume of LLW destined for geological disposal has not been specified. The small quantity of the LLW UK destined for disposal by deep geological disposal is largely made up of reactor core graphite and effluents with a potential for high concentrations of alpha activity and/or long-lived radioisotopes.

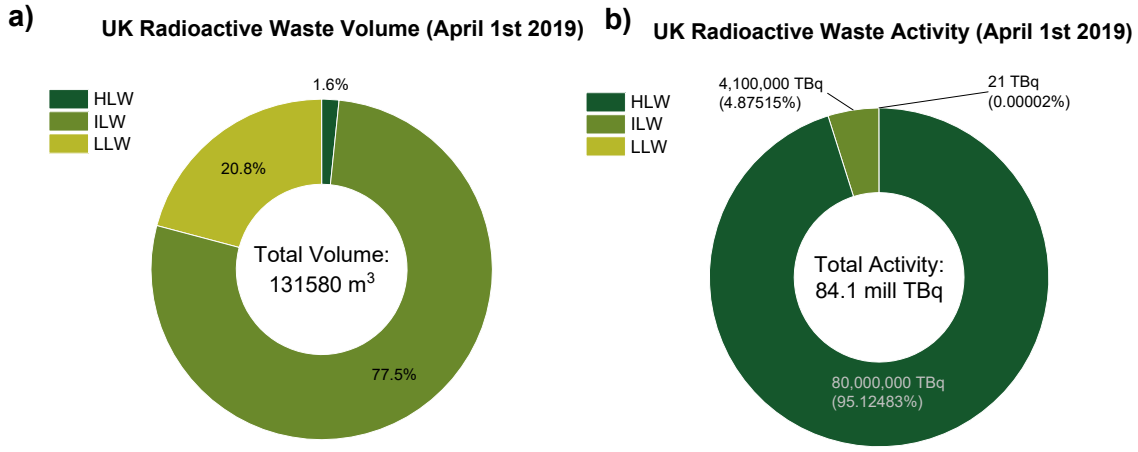


Figure 2.4: a) UK radioactive waste by volume b) UK radioactive waste by activity, based on data sourced from [6].

By both volume and mass, ILW comprises the majority of the UK's current waste inventory destined for disposal in the GDF, as in Figure 2.4a. ILW comprises more waste packages for disposal and will command a larger proportion of the underground footprint than HLW or LLW. However, as displayed in Figure 2.4b, of the ~84 million TBq of activity contained within the inventory as of April 1st, 2019, approximately 80 million TBq is attributed to the 1.6 % (by volume) of HLW. ILW contains approximately 4.1 million TBq of the inventory's activity, or 40 TBq per m^3, considerably less than the ~39,000 TBq.m^{-3} of HLW.

The main source of future arisings of HLW is the ceasing of UK reprocessing activities, the last of which at the Magnox reprocessing plant, are scheduled to finish operation in July 2022 [25], [53]–[55]. The total volume of HLW is anticipated to decrease due to evaporation, vitrification, and exports of ∼267 m^3 to overseas customers, resulting in a packaged volume of 1,500 m^3 HLW contained in ∼7,700 packages for disposal. The decommissioning of existing reactors and other facilities is expected to increase the ILW contribution by 114,000 m^3, 78 % of the total future arisings of ILW in the UK. Overall, it is anticipated that over the next century, the total volume of ILW will peak at ∼499,000 m^3. By 2100 ILW will contain about 1,000,000 TBq of activity; the activity of the HLW will be about 12,000,000 TBq at this time [6].

Spent Nuclear Fuel

SNF is not currently designated as HAW, and hence is not currently set for disposal in a GDF. As of April 2019, there's approximately 6,100 tHM (tonnes of heavy metal) of UK-owned SNF in reactors or storage, with a further 2,200 tHM in future arisings based on the UK's current strategy. Should future policy designate SNF as radioactive waste, the disposal of SNF in a GDF will have a significant impact on its underground footprint.

2.3 Disposal Options for Radioactive Waste

2.3.1 Waste Disposal Concepts

The UK has clearly identified and defined its radioactive waste streams (as well as those materials yet to be defined as waste), and has settled upon disposal routes which are readily available or are continuing to be developed. Throughout the UK's history in the nuclear industry, a number of waste disposal methods have been considered, and will be discussed briefly herein.

Between 1949-1982, the UK advocated and utilised so-called "sea dumping" of low- and intermediate-level waste, in which packages were disposed of at sea, where it was expected that

they would implode and disperse, or remain on the sea-bed to decay [56]. Approximately 35,000 TBq of radioactivity was disposed of around the UK coast, primarily at depths below 2000 m. The UK's obligations under the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LC '72) and Convention for the Protection of the North East Atlantic (OSPAR) since 1972 have prevented the seabed disposal of radioactive waste (not to be confused with inshore geological disposal from a facility accessible from land) [57]–[59].

Internationally, many more concepts for disposal have been considered as part of radioactive waste management strategies, including [56]:

- Disposal in outer space- prohibited by cost and safety issues.
- Rock melting- which has not been significantly investigated[56].
- Disposal at subduction zones- though is prevented by geographic restrictions and/or international resolutions.
- Deep well injection- implemented by Russia since the 1950s; also a short-lived programme based out of Oak Ridge National Laboratory scrapped in 1970s.
- "Guardianship" in monolith stores- long-term surface storage which has been investigated under French law, however monoliths not currently being pursued as a viable HAW management activity [56], [60], [61].

As previously mentioned the UK readily disposes of LLW, and some short-lived ILW, at near-surface disposal facilities suhc as those at Drigg, Cumbria (Low Level Waste Repository) and Dounreay, Caithness. Typically, a near-surface disposal facility comprises a number of engineered vaults or trenches, at the surface or near-surface depth (10s of metres), which hosts cement backfilled ISO containers of LLW. Near-surface disposal is suitable for a large proportion of the UK's LLW, the remainder of which, along with HAWs (ILW and HLW) are destined for geological disposal.

2.3.2 Geological Disposal

As alluded through 2.1 and 2.2, HAW will be disposed of via deep geological disposal. In line with some international programmes the first Committee on Radioactive Waste Management (CoRWM) recommended geological disposal as the end point in the long term management of HAW in the UK [16]. CoRWM recommended implementing geological disposal as soon as practicable, believing it to be the best available approach to waste management which would reduce any burden on future generations. This was informed by multi-criteria decision analysis that considered exposure in the far future, and the risks of geological disposal compared to long-term storage.

The UK and Welsh Governments, and Northern Ireland Executive support geological disposal of HAW in concurrence with international consensus [62], [63].

2.3.2.1 The Geological Disposal Facility

Geological disposal refers to the emplacement of solid radioactive wasteforms in an engineered underground facility, within a stable geological setting, that provides " a unique level and duration of protection for high-activity, long-lived radioactive waste" and isolation from the accessible biosphere, without impacting on background levels of radioactivity,[64], [65] an exampl of which is demonstrated in Figure 2.5 .

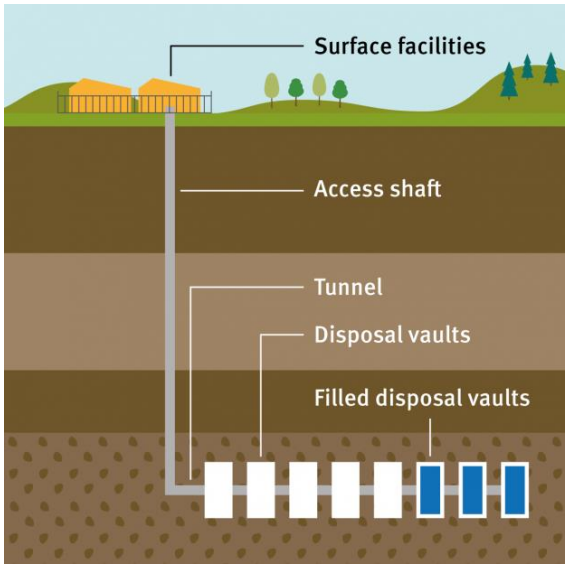


Figure 2.5: Basic schematic of a geological disposal facility [66]

A geological disposal facility (GDF) will be made up of natural and engineered components, at a depth of between 200 m and 1000 m, designed to provide a multi-layered barrier against the release of radionuclides from disposed wasteforms. This will typically comprise a number of tailored galleries excavated at the depth of emplacement, accessible by shaft or drift tunnel. The engineered barriers are enveloped in a suitable "geological cocoon" exhibiting characteristics that mitigate issues such as the ingress of groundwater towards disposal containers (facilitating significant decay of radionuclides) and the movement of radionuclides once the engineered barriers have failed and a groundwater pathway has formed between the wasteform and the geosphere. The geological setting may possess properties that restrict groundwater flow to diffusion, such as "self-sealing" or creep behaviour, or contain pores capable of adsorbing important radionuclides, which restrict the level of activity able to reach the biosphere. A minimum depth of 200 m ensures that the repository should not be affected by forecasted glacial and surface erosion, whilst depths below 1000 m offer little advantage due to increased construction costs and engineering challenges.

A GDF is required to isolate HAW from mankind until the radioactivity has decayed to levels where the risk to future generations is acceptably low. It is likely therefore, that a GDF will need

to safely contain radioactive materials for hundreds of thousands of years. As such the choice of geology will be crucial in achieving this. The UK possesses all 3 of the generic geological settings which have been explored as potentially suitable for the siting of a GDF, as described in 2.4.1.

2.3.2.2 History of UK Geological Disposal

Multiple attempts have been made to implement geological disposal in the UK. The initial intention was to focus on a GDF for HLW, which collapsed, leading to the formation of NIREX (see below) to focus on the disposal of ILW and LLW in a GDF [56]. Nuclear Waste Services (NWS; formerly RWM) are the UK's delivery body for geological disposal and will need to learn from the failings of previous programmes if they are to successfully select a site for the repository. The following is an overview of the phases of the UK's attempt to implement geological disposal.

Phase 1: Feasibility Studies

Early proposals for the disposal of radioactive waste in the UK included the use of existing excavation sites such as mines and their associated shafts. However, the publishing of the sixth report of the Royal Commission on Environmental Pollution in 1976 began the first significant phase of UK exploration of geological disposal [67]. The report called for a decade of feasibility studies into the potential disposal methods of heat generating wastes, before any commitment to further large scale fission programmes. Subsequently the UKAEA selected 127 areas of suitable geology for further investigation [68].

Between 1978-81, planning applications were made to local authorities across Scotland and England to conduct borehole drilling investigations, including the Mulwharchar Hill area of Ayrshire and Altnabreac region of Caithness, situated close to the Dounreay site, as well as areas in Northumbria, Somerset, Leicestershire, Bristol and Nottinghamshire [56]. Major opposition contributed to Ayrshire County Council failing to obtain planning permission, despite an appeal and the first public consultation of its kind. Borehole drilling at Caithness was accepted and conducted. Public perception of UKAEA's plans were the demise of this scheme and led to the

Government abandoning the programme of test drilling in December 1981.

Phase 2: NIREX

In 1982 the Nuclear Industry Radioactive Waste Executive (NIREX; from 1985 known as United Kingdom Nirex Ltd), was founded to provide guidance to waste producers on radioactive waste packaging and to identify suitable host environments for disposal. NIREX efforts focused initially on near-surface disposal of LLW, whilst acknowledging the need for a deep repository for ILW, though proposals for separate ILW and LLW host sites faced similar opposition and public pressures [56]. In 1983 NIREX proposed the use of a disused anhydrite mine in Billingham, County Durham, for the disposal of ILW and a site in Elstow, Bedfordshire for the near surface burial of LLW and short-lived ILW, to help extend the lifetime of the Drigg disposal facility [56]. Elstow was shortlisted along with three further sites in Lincolnshire, Essex and Humberside as potentially suitable sites for ILW in 1986 and Special Development Orders were granted. Significant protest and public and political opposition ensued, and by May 1987 proposals for separate facilities was abandoned.

NIREX published "The Way Forward" in November 1987 as a tool for consultation that considered the development of a deep underground repository for both LLW and ILW, and provided an overview of the principles of geological disposal, describing a range of repository concepts and a breakdown of the site selection process, involving national survey and evaluation, site identification and site confirmation [69], [70]. The report proposed three broad options for disposal: disposal under the seabed with access from offshore, disposal under the seabed with land access and disposal under land.

Local authorities generally reacted positively, with a clear dislike for the option of under-seabed disposal [71]. By 1989, two of ten proposed sites were considered for further investigation, both near existing nuclear sites, at Sellafield and Dounreay. Following two years of study, with 60 % of the UK's radioactive waste located at Sellafield and a 74 % majority of Caithness voters opposed to disposal in their area, Sellafield was selected as NIREX's preferred site in 1991 [69].

NIREX submitted a planning application to Cumbria County Council for the development of an underground rock characterisation facility at Sellafield site in 1994, to continue investigations at depth. This proposal was rejected, leading NIREX to lodge a planning appeal in February 1995 [72]. This was subsquently rejected by then Secretary of State for the Environment, John Gummer, with concerns over scientific uncertainties, technical deficiencies, and a lack of understanding of the regional hydrogeological system cited.

Phase 3: The Committee on Radioactive Waste Management

Following the 1997 General Election, NIREX reviewed the events of their previous attempt and found key issues requiring significant improvement included their decision-making processes, organisational structures and the behaviour of organisations including their conduct and consideration for stakeholder engagement. Congruently, the House of Lords Select Committee on Science and Technology conducted an investigation into radioactive waste management in the UK, which called for widespread public consultation for future programmes, becoming the focus of the 2001 "Managing Radioactive Waste Safely" publication and consultation [57].

Following this, the Government established an independent committee for reviewing radioactive waste management options, the Committee on Radioactive Waste Management (CoRWM), whose objective was to generate practicable recommendations and conduct themselves transparently to help inspire public confidence. In 2006 CoRWM published its recommendations, stating that they considered deep geological disposal to be the best available solution for the long-term management of the UK's HAW [16]. Following the work of CoRWM, the Government published a white paper related to implementing geological disposal [62]. Copeland Borough, Allerdale District and Cumbria County Councils all expressed an interest. Over 70 % of the waste due for disposal was expected to arise at the Sellafield site in Copeland. These authorities established the West Cumbria Managing Radioactive Waste Safely Partnership to deliberate formal participation in the siting process. On the 30th of January 2013, Copeland and Allerdale Borough Councils voted in favour of moving onto the stage 4 of the site selection process, which comprised desk-based studies in participating areas [62], [73]. However, on the same day

Cumbria County Council voted not to proceed, citing concern over the right of withdrawal. All 3 authorities were required to be in agreement for the development to proceed to the next stage, effectively ending this phase of the siting process [74]. Following this, the Government opted to initiate a review of the GDF siting process, generating the 2014 White Paper in the process [75].

Phase 4: RWM Site Selection

The UK is presently engaging in the a new phase of site selection for the GDF. This was initiated in 2014 with the publishing of the "Implementing Geological Disposal" white paper, setting out a renewed process for the siting of a GDF, updated by the 2018 policy framework "Implementing geological disposal- working with communities" which outlined a consent-based site selection process, the planning regime and how the GDF would be regulated [19], [75]. This new approach relies on community voluntarism, as recommended by CoRWM, and sets out a programme of engagement with those parties interested in hosting the GDF. Presently NWS are working with communities to generate working groups and subsequently community partnerships. These provide the key mechanism for the communication of plans, practices and progress to local communities whilst receiving their feedback on matters related to the development of the GDF. Working groups in Copeland, Allerdale (both Cumbria) and Theddlethorpe (Lincolnshire) had been formed as of October 2021 [9], [76], [77]. Since then, Copeland have agreed to participate in two community partnerships, each focused around one a search area identified within Copeland (Mid Copeland and South Copeland respectively), with a further community partnership developed in Allerdale in January 2022 [10], [78]–[80].

2.3.2.3 International Geological Disposal

Many countries are in the process of developing GDF programmes for the disposal of higher activity wastes or spent nuclear fuel. Table 2.2 provides a brief overview of the progress made in a number of international programmes to date [81]–[96].

Table 2.2: Overview of International Geological Disposal Programmes.

Country	Waste	Geological Setting (Selected or Investigated)	Progress To Date
Belgium	HLW*	Plastic Boom-clay	Belgian regulator (FANC) supports geological disposal in 2020, awaiting public consultation.
Canada	SNF	Canadian Shield and sedimentary geologies under consideration	Nine volunteer communities, all in Ontario, currently engaging with NWMO to identify a suitable site for their DGR.
China	HLW	Granite	Ground broken on the Beishan Underground Research Laboratory in June 2021.
Czech Republic	HLW and SNF	Granitic rocks	In December 2020, the Czech Cabinet approved a shortlist of four sites for their DGR.
France	HLW and long-lived ILW	Mudstone	Site selected in Meuse region and licence application preparation ongoing.
Finland	SNF	Granite	Excavation of disposal tunnels commenced in May 2021 at Onkalo, Olkiluoto.
Germany	HLW	Previously earmarked Gorleben Salt Dome	Formally re-launched site selection process in September 2020.
Japan	HLW	Crystalline or sedimentary	Two municipalities (Suttu, Kamoeni) accepted literature surveying to re-initiate siting process in October 2020.

Netherlands	HLW	Clay	Developing research programme for the development of a GDF.
Russia	HLW and long-lived ILW	Granite	The Nizhnekasky Granite Massif in Kransoyark has been confirmed and approved for repository, with NO RAO aiming to build an underground research laboratory by 2024.
South Korea	HLW (possibility for SNF)	Crystalline rock	Plans to extend storage facilities and select a site for a GDF by 2028.
Sweden	SNF	Granite	Forsmark site selected and awaiting permit by Swedish Government for construction of GDF.
Switzerland	HLW	Opalinus Clay	Multiple sites being investigated for anticipated selection in 2022.
USA	HLW *(Military Waste)*	Mixed Tuff	Yucca Mountain project vetoed, awaiting further development, though policy still to develop a GDF in the USA. *(Waste Isolation Pilot Plant operated at Carlsbad, New Mexico since 1999.)*
UAE	TBC	Six environments identified including evaporite and high-strength rock.	Radioactive Waste Management Organisation established in 2021. Regulator FANR have developed initial draft regulation.

* Has not officially decided upon final disposal route for high-level and long-lived wastes.

2.4 Geological Settings for a GDF in England or Wales

The choice of geology will be critical to aspects of the design, construction, and operation of a GDF, however a best geology approach is not one being considered by the UK government [97]. The timescales over which a GDF is expected to contain and isolate radionuclides far exceed the capabilities of man-made engineered materials, which places an onus on the role of the geological setting and its ability to remain stable for millions of years [98]. The primary duty of the geological setting is therefore to maintain a physical barrier which isolates waste, whilst providing a setting which is chemically and mechanically suitable for the preservation of the engineered barrier materials utilised [99].

2.4.1 Generic Geological Settings

Initially as many as ten geological environments were considered for the UK's GDF [100]. At present, three generic geological settings have been proposed as potential host environments for the repository: hard, fractured, high strength rocks (HSRs), lower strength sedimentary, clay-like rocks (LSSRs) and evaporite salt environments [101]. As the UK programme relies on voluntarism, all three geologies have been considered in a national geological screening across England, Wales and Northern Ireland to support early engagement with interested parties and local communities [102]–[104]. Sections 2.4.1.1-2.4.1.3 provide brief summaries of each generic setting, which are distributed across the UK (described in 2.4.2). A number of key characteristics of the proposed geologies are discussed (2.4.3) and the key points relevant to the regulation of geological disposal highlighted thereafter (2.5).

2.4.1.1 High Strength Rocks (HSR)

High strength or hard rocks (HSR) comprise a number of geological environments, including metamorphic, crystalline igneous and aged sedimentary rocks. In petrological terms, a rock

mass made up of HSR is likely to comprise an array of different environments with similar mechanical properties [98]. Compositional variation can lead to variability between and within differing lithologies, which could render specific sites unsuitable for the significant excavation required in the construction of a GDF [105]. HSRs are high strength, low permeability media, in which groundwater flow is typically dominated by advection via a network of fractures, with little to no diffusion through the low permeability matrix.

The most prevalent HSR lithologies for geological disposal include intrusive and extrusive igneous, low grade metamudstone and crystalline medium-high grade metamorphic rocks. Most higher strength rocks are formed as a consequence of exposure to mid-crustal conditions (temperatures in the region of 400-700 °C, and pressures between 3-10 kbar). Extrusive igneous rocks, largely metavolcanic slates, originate from erupted lava and volcanic debris such as ash flow tuff and tuffaceous clastic sediments that have undergone low grade metamorphism. Metamorphic lithologies are coarser in grainsize than lower grade materials and are derived from protoliths of sedimentary or igneous rocks undergoing changes in temperatures and pressures [98]. Igneous intrusions originate as magmas in the earth's crust, and form dykes, sills and plutons of mainly granitic minerals, such as feldspars and quartz. Disposal programmes in Finland, Sweden, Argentina and Canada are all at different stages in the process of implementing geological disposal within HSR environments [101].

2.4.1.2 Lower Strength Sedimentary Rocks (LSSR)

Lower strength sedimentary rocks (LSSRs) are typically fine grained sedimentary or mudrocks formed by the deposition, typically underwater, of very fine-grained particles. The majority are made up of clay minerals, with approximately 30 wt% of the deposit with grain sizes <60 μm [98], [106]. Marine deposits tend to form in layers where properties are homogeneous over regions in excess of hundreds of square kilometres.

LSSRs are geologically younger sedimentary rocks, and the movement of fluid is dominated

by diffusion through its network of pores. Clays offer lower permeability than HSRs, but are more challenging to engineer [98]. LSSRs tend to form part of a diverse sedimentary sequence, comprising indurated siltstones, of mineral particle size 2-60 μm, clays, with mineral particle size <2 μm or mudstones which can dictate its physical behaviour [106]. These classes differ largely in their compaction, lithification and to what extent they undergo alterations [107]. LSSRs can be sufficiently weak that fractures in the geology at repository depth are able to self-seal, a favourable trait for a GDF host environment. The mechanical properties of different types of LSSR are not always equivalent however, and the hardness and brittleness of some clays can influence the rate of fracture recovery [108].

LSSRs, are highly abundant in many regions across the UK [98]. Site investigations in Belgium, France and Switzerland have centred on the utilisation of LSSRs as a host, including Boom and Opalinus clays and Callovo-Oxfordian mudstones [109].

2.4.1.3 Evaporites

Evaporites are typically defined as water soluble mineral salts, such as anhydrite, gypsum, sylvite, halite or minerals that result from the evaporation of saline bodies of water such as sea water, "marine evaporites" or short-lived inland bodies [98]. Sylvite and halite are of particular interest for a GDF, due to their characteristic aridity and ability to close fractures.

Though initially formed as horizontal salt beds, plastic deformation and variability in density often results in the vertical flow and growth of salt pillars. Once the overlying sediments have been penetrated sufficiently by the pillar, the formation of a dome-shaped salt diapir (sometimes over 1 km laterally) commences.

Evaporites exhibit little sensitivity to detailed mineralogy or whether it is found in the form of a diapir or lateral bed. This may however impact on the extent to which a GDF would need to be excavated as a single, or multi-level repository [110]. The majority of the UK's evaporite reserves are contained within aged depositions, originating from a number of inland terrestrial basins,

with thicknesses of 400 m recorded at Wilkesley; much larger deposits in excess of 300,000 km^2, up to 3500 m thick have been identified in the USA [98], [111]. It is noted that the demand for salt as a natural resource is a challenge with respect to human intrusion of any potential GDF in an evaporite, which is less likely to be associated with the other generic settings.

The Waste Isolation Pilot Plant (WIPP) repository for transuranic waste is the only such facility actively operating and disposing of waste, whilst the Gorleben salt-dome, a proposed location for Germany's high level waste repository was closed and removed from the list of potential sites in September 2021 [112].

2.4.2 Distribution of Geological Settings in the UK

A series of 13 regional guides, detailing the composition of each region's geology, was produced for areas in England, Wales and Northern Ireland, as part of the UK's National Geological Screening Programme [113]. The screening identified and explored the natural processes and resources present in each region. Screening reports provide an overview of the geology of the regions, including potential rock types of interest (PRTI), a description of the lithology, the extent to which the rock extends and their principal characteristics. Regions were subdivided into basins, associated with thick, more complete rock units, and thinner, less complete sedimentary successions known as blocks. PRTIs were compiled stratigraphically and their regional distribution at depths of 200-1000 m mapped as in Figure 2.6.

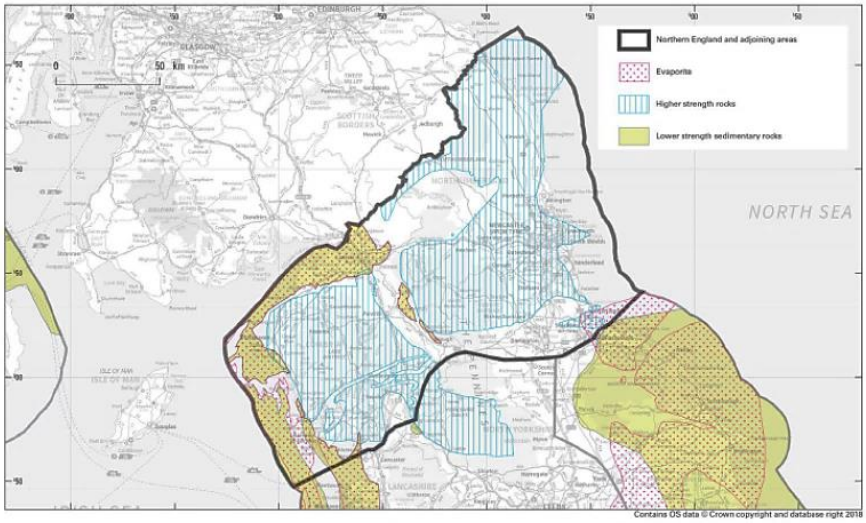


Figure 2.6: Distribution of geological settings in the Northern England region according to the NGS [102].

2.4.3 Characteristics of Geological Settings

RWM derived a number of geological attributes relevant to the long-term safety of a GDF. These attributes enable the identification of suitable geological areas and the choice of engineered barriers, and include:

1. Rock type
2. Rock structure
3. Groundwater
4. Natural Processes
5. Resources

Each of these attributes is influenced by the inherent physical, thermal and chemical properties and characteristics of the geological setting. The physical and geomechanical properties in

particular contribute to the 17 design requirements for a GDF [114]. A number of the key properties which aid the assessment of site suitability are summarised below.

Unconfined Compressive Strength

Unconfined or uniaxial compressive strength (UCS) is a common descriptor for specifying a rock's mechanical strength and will be relevant in establishing the engineering limits and requirements of a potential GDF site . It corresponds to the maximum axial compressive stress a cylindrical material sample can endure, and has been categorised, by the International Organization for Standardization (ISO), as in Table 2.4 [115]. For an environment to be considered suitable for geological disposal it is necessary for it to be mechanically stable enough to support excavations at GDF depth; if required engineered lining materials can be utilised, however consideration must be given to the effects this may have on the GDF's evolution.

Table 2.3: ISO categorisation of Unconfined Compressive strength (UCS).

UCS/ MPa	Classification
0.6-1	Extremely Weak
1-5	Very Weak
5-12.5	Weak
12.5-25	Moderately Weak
25-50	Medium Strong
50-100	Strong
100-250	Very Strong
>250	Extremely Strong

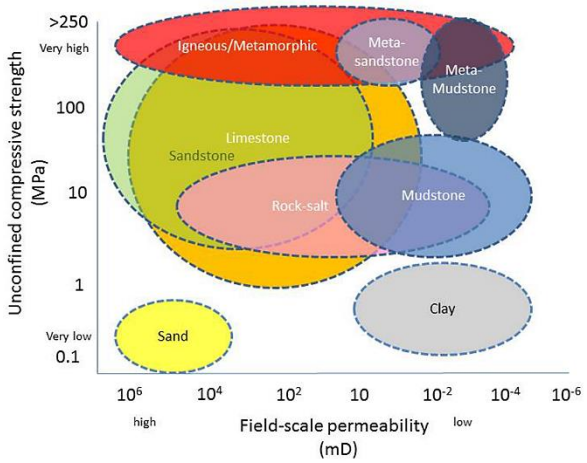


Figure 2.7: The unconfined compressive strength (UCS) of a number of candidate host geologies and the scale over which their permeability varies in the field [98].

HSRs in the UK exhibit variable UCS close to the surface, from extremely weak to extremely strong, and it is likely that any site identified for a UK GDF will comprise a mixture of strengths. It is important to note that GDF depth and pressure could significantly influence a geology's properties, and settings which exhibit significant fracture at near-surface level may demonstrate self-sealing at increasing depth.

Table 2.4: Characteristic unconfined compressive strength (UCS) values for a number of high strength rocks.

Geology	UCS/MPa
Extrusive igneous	50->250
Intrusive igneous	100->250
Medium to high grade metamorphic	50->250
Low grade metasandstone	25->250
Limestone/chalk	5-250
Sandstone	<1-50

HSRs generally exhibit moderate to strong UCS (see Table 2.4), which is favourable from an engineering standpoint, allowing for larger galleries to be excavated. This variability, the impact of GDF conditions and factors such as the degree of fracturing and mineral decomposition will determine to what extent the environment will be self-supporting during excavation [98], [99]. Clays and mudstones (LSSRs), generally exhibit lower mechanical strength, with UCS in the range of very weak to medium strong; mudstones display unconfined compressive strengths between 5-50 MPa, where clays, including those that have undergone severe compaction, perform within the range of 1.15-25 MPa [98]. Under saturated conditions, claystone becomes weaker, with the UCS decreasing to as low as 20 % of the unsaturated level [116]. The extent of clay saturation also impacts on its response to a change in thermal conditions, exhibiting brittle tendencies with increased temperature. This is due to the over-pressurisation of pores and reduction of cohesion resistance of the films between solid particles which is induced by increased temperatures [116]. In the absence of significant saturation, an increase in the exhibited strength is observed with increased temperature, as pore strength consolidates and friction resistance between particles increases. Mechanically, evaporites are the weakest of the three generic geological settings, as exhibited in Table 2.5 [117]. Halite and sylvite (potash) are the most

abundant examples suitable for geological disposal, though only exhibit a UCS of up to 30 MPa, typically in the region of 14-25 MPa. Mechanically stronger examples such as anhydrite, with compressive strengths of 95-105 MPa have been noted, though their scarcity, and propensity to swell and dissolve, may induce damage to constructions [106], [118].

Table 2.5: Values of UCS for multiple evaporite environments. [98], [106]

Evaporite	UCS/MPa
Halite (Rock Salt)	12; 5-25
Gypsum	25-30
Sylvite (Potash)	30
Anhydrite	95-105

However it is not envisaged that low UCS would impact on the ability to excavate easily, given the slow rates of evaporite deformation anticipated during the GDF's operational period [119].

Faulting, Fracture Formation and Creep

The historic impact of processes such as hydrothermal metamorphism, and excavation induced damage can result in the formation of faults and zones of high shear stress in HSRs [98]. Fractures present will be spatially irregular and exhibit variable geometric and hydraulic properties due to interplay between past and present stresses, the mechanical properties of the rock, fracture interactions and the distribution of flaws [120]. Fracturing provides a pathway for advective groundwater flow; this type of pathway facilitates an increase in local permeability, particularly in lithologies at depths and pressures where they are not anticipated to self-seal [117]. This may be an important factor in the isolation of radionuclides and maintenance of EBS material integrity.

Both LSSR and evaporite geologies are capable of exhibiting so-called “creep” or "self-sealing" behaviour, the tendency for time-dependent strain, which is caused by shearing at the micro-structural

level during compression under drained conditions, and macro-strain in undrained conditions [121]. It is postulated to occur over three stages: elastic strain and time dependent deformation, constant creep and strain rate acceleration to failure (see Figure 2.8) [106]. The "self-sealing" capability of many LSSR and evaporite environments enables groundwater flow to be limited to diffusion, as they deform under the constant load of the surrounding environment. Evaporites tends to exhibit the highest levels of creep, and HSRs are unlikely to display substantial creep, though minimal creep due to microcrack growth is possible [98].

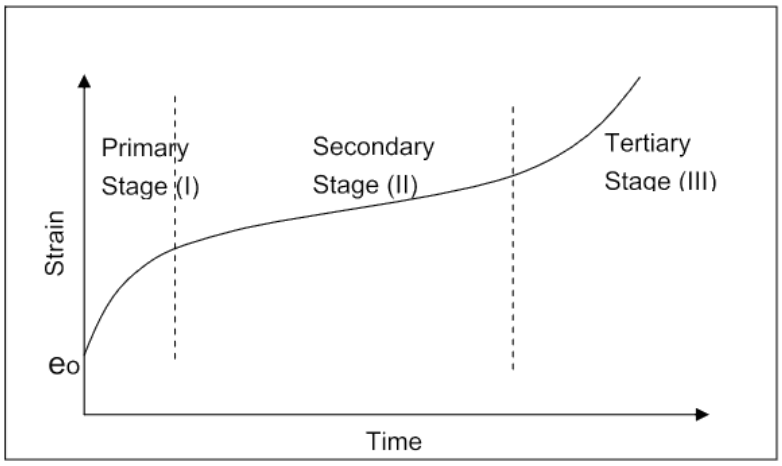


Figure 2.8: The three stages of creep behaviour, as observed in some LSSR and evaporite settings [106].

In evaporites, the absence of mobile groundwater means that minimal inflow will occur during the operational period and self-healing of any excavation damaged zone by creep can occur. Rates of creep vary with depth, age and mineral content; at the Gorleben exploratory mine, situated within a large salt diapir, rates of 1-1.5 mm.yr^{-1} were observed in younger regions, and to 8.5-10 mm.yr^{-1} in older areas [106].

Creep may limit the time over which excavations remain open for emplacement without refurbishment or reinforcement, require the use and replacement of structural supports and hinder the ability to retrieve waste once it has been disposed of. In some evaporites, supports in excavation roofs, side walls and shoulders, in the form of rockbolts or mesh wire walls would

be suitable for short term activities, or methods such as wall scraping are utilised to mitigate creep-induced issues [106].

Porosity and Permeability

Porosity may play a critical part in facilitating or mitigating radionuclide release from the GDF, and is defined as the fraction of the material that's occupied by void space.

The porosity of HSRs is highly variable, and in weaker strength rocks such as limestone and chalks, can dictate the mechanical properties such as the UCS [122]. HSR porosity varies in the range of 0-50 %, though most frequently porosity between 0-10 % is observed. This depends on the degree of metamorphic alterations undergone by the rock; some granitic bodies experience severe hydrothermal modifications, which causes feldspars and micas present within the matrix to be replaced by mechanically weaker, porous clay minerals.

Porosity tends to vary from low (5-10 %), to very high in LSSRs, with some clays known to exhibit up to 70 % porosity; typical values obtained by Nagra fell below 20 % [108].

In the shallow subsurface region, halite can exhibit extremely low porosity, <0.1 %, with some estimates of undisturbed halites stating it exhibits the equivalent of 0 % connected porosity [98]. Despite this, small unconnected inclusions such as brine pockets, varying from micron to metre scale may be present [123]; in areas close to excavation walls of the Saldado formation at WIPP, porosity up to 3-5 % porosity has been estimated [106], [107].

In general, a higher porosity will mean higher permeability [124]. HSRs have been shown to exhibit very low to high permeabilities, with extreme values of 10^{-8} millidarcy (mD; 1 millidarcy is equivalent to 9.869233×10^{-16} m^2) and 10^6 mD in low grade metamudstone/intrusive igneous settings and extrusive igneous environments, respectively. The formation of fractures, the prospect of brittle and ductile failure at GDF depth in settings such as cretaceous limestone and the effects of diagenesis cement precipitation, particularly in sandstone environments, all drive an increase in field-scale permeability.

Creep will contribute to the low permeability of LSSRs and evaporites, restricting groundwater flow to diffusion. Permeabilities as low as 10^{-4}-10^{-6} mD have been observed in claystone fracture zones after a matter of months [125]. Generally the permeability of LSSRs is variable, in the region of 10^{-8}-100 mD, decreasing with increased depth [98], [106], [126], [127]. Variability can be attributed to the direction of flow, lower values obtained perpendicular to LSSR bedding, though the presence of higher permeability interlayers/inclusions may lead to localised regions of higher permeability.

The primary permeability of evaporites generally falls in the range of 10^{-6}-10^{-5} mD, extending to $<10^{-3}$-10^{4} mD on a field scale, with some tighter halites exhibiting permeabilities as low as 10^{-7}-10^{-9} mD [98], [128].

Low permeability and porosity in evaporite systems indicates there will be no dominant pathway for groundwater flow; essentially no groundwater is expected to flow through evaporite systems. Inclusions have been observed to remain immobile under natural conditions and the inclination for creep in certain geologies ensures that should there be any fluid flow, it will be by diffusion or dissolution, as advective routes are sealed.

Surface processes such as liquefaction and coseismic consolidation can contribute to an increased feed of water from unconsolidated near surface materials, thus a geology with low permeability is advantageous [129], [130]. High porosity can also be beneficial; the mineralogy of LSSRs, specifically the presence of smectite within a layered mineral structure, can lead to absorption of water within its crystal structure and swelling [106]. These pores can also be highly adsorbant to important radionuclides, preventing the migration of a proportion of these radionuclides once they've been released from the GDF.

Thermal Conductivity

A GDF will host some high-heat generating wastes (HHGW). The decay of short and medium-lived fission products leads to the emission of radiation, often in the form of alpha or beta particles, or gamma radiation, neutrons or x-rays, which increases the temperature in the absorbing

medium via conduction. The performance of a number of engineered barrier materials and the effectiveness of the geological barrier, may be affected by an increase in temperature. As such the thermal conductivity of the geology and the ability to dissipate decay heat may be important to maintaining GDF performance. The thermal properties of the geological setting will feed into multiple aspects of the waste lifecycle, including waste package specification and GDF design to minimise the potential for adverse effects. Temperature can also affect the rate of chemical reactions in and around the GDF, including degradation of engineered barriers, and could lead to the establishment of temperature differentials in groundwater in the surrounding rocks. Because groundwater density decreases with temperature, buoyant flows could be established, with warmer groundwater in the vicinity of the GDF rising upwards through cooler groundwaters.

Table 2.8 summarises the average thermal conductivity values for examples of each generic geological setting considered for a UK GDF, sourced from international waste management programmes [131]. In each case there is variation as thermal conductivity is a function of temperature e.g. Finnish granite exhibits a marginal decrease in conductivity with an increase in temperature. Generally evaporites exhibit the highest thermal conductivity, followed by HSRs and LSSRs.

Table 2.6: Measured thermal conductivities for international disposal concepts in each geological setting

Host Environment	Geology	Country	Thermal Conductivity/ $W.m^{-1}.K^{-1}$
HSR	Granite	Finland	2.3-3.2
		France	2.4-3.8
		Sweden	2.45-2.9
HSR (Unsaturated)	Tuff	USA	0.99-2.09
LSSR	Clay	France	1.9-2.7
		Switzerland	1.8
		Belgium	1.7(H); 1.25(V)
Evaporite	Halite	USA	3.09-3.37

Groundwater Chemistry

Groundwater chemistry near the repository will be dominated by the chemical composition of the geological setting. Knowledge of the geological setting is important therefore to understanding repository conditions and to help facilitate engineering choices that are compatible with the environment.

Hydrochemistry is site specific, thus cannot be easily generalised for all settings of a particular type. Historical groundwater flow as well as the hydrogeology of the larger region will contribute to groundwater behaviour and the performance of engineered barriers. Slower moving groundwaters, as expected in diffusion dominated LSR environments, tend to mirror the mineralogy of the surrounding environment, which in turn can impact upon the redox potential of the groundwater. Deep groundwaters will comprise larger concentrations of chloride

containing compounds, or in some cases sulphides both of which may promote the onset or increase the rate of corrosion of some engineered barrier materials such as stainless steel and copper. The swelling properties of some barrier materials may also be inhibited in the presence of highly saline groundwater [132].

2.5 Key Points of Importance for the Regulation of a GDF

The GDF is a unique, underground, 3-dimensional facility which will bring with it a number of challenges for nuclear regulators, in terms of how best to apply a regulatory framework which sufficiently controls the design, construction, commissioning, operation and decommissioning/closure of the facility. The current framework, discussed in Chapter 7, includes a number of requirements that may need to be amended or could be deemed unsuitable for applying to a geological disposal facility. For example, communicating the underground footprint, which extends laterally much further than the surface site boundary, below land not owned or leased by the licensee and ensuring safety underground, unlike any previous nuclear installation licensed in the UK, will require tailored regulatory solutions.

The regulators of the UK GDF will need to be assured of a site's suitability for hosting a geological disposal facility before granting the permissions required for the GDF to commence physical development. The licensee of the GDF site will need to convince the regulators through safety case submissions that the development of a GDF in the chosen geology is demonstrably feasible and safe, that workers, the public and the environment will all be sufficiently protected. From a security and safeguards standpoint, the choice of geology could impact how likely unintentional human intrusion to the site is in the post-closure period.

With respect to the waste destined for geological disposal, the regulators will be concerned with several issues including control over what is sent to the GDF, and will also need to be satisfied that waste being disposed of meets the licensee's WAC as set out in the safety case.

2.6 Areas for Further Research

Once the site for the GDF has been selected, further research may be needed in the following areas, many of which may depend on the geology of the site selected:

- surface and intrusive investigations to assess the suitability of the geology in the proposed area, which could impact on the expectations or limitations placed upon the design of the GDF and in turn, could impact on how much, and what type of waste could be disposed of in the GDF.
- the impact of the geological conditions at repository level on packaged wasteforms, once the barriers around the wasteform have failed.
- the development of the UK's inventory for disposal to aid the development of the GDF and ensure it can accommodate he necessary waste streams.
- site specific modelling will provide a more complete picture of the potential evolution of the geology throughout the lifecycle of the GDF.

The GDF will as alluded, comprise a number of man-made and natural materials utilised to reduce the likelihood of radionuclide release from HAW in the GDF. In Chapter 3, the concept of the engineered barrier system (EBS), which will perform multiple functions in the disposal of HAW in the GDF, is explored.

Chapter 3

Engineered Barriers Systems for Geological Disposal

3.1 Introduction

The critical safety functions required of a geological disposal facility (GDF) are isolation and containment, and will be provided by combination of geological and engineered barriers. Chapter 2 summarised the concept of geological disposal in a UK context, to understand what exactly will be disposed of in the GDF, and what type of environment is being considered for hosting of the repository. The GDF will comprise a multi-layered engineered barrier system (EBS) which will facilitate significant radionuclide decay and provide a defence-in-depth that gives the public confidence in the long-term performance of the GDF. The properties of the waste and the geological setting, and their interactions with engineered barrier materials will be significant to the development of the short- and long-term post-closure safety cases, thus a detailed understanding of engineered barrier systems and suitable materials is vital. Chapter 3 explores what constitutes an engineered barrier system and describes the properties of engineered barrier materials currently utilised or proposed for the UK's management of radioactive waste. The information contained in Chapters 3 and 4 have been peer-reviewed and published as a

review paper based on the role and performance of engineered barriers [133].

3.2 The Engineered Barrier System

The GDFs engineered barrier system (EBS) will comprise a collection of materials specifically selected to provide defence in depth against the migration of radionuclides away from the GDF "near field" [134]. The effectiveness of these barriers will rely on the inherent properties of materials, individually and in combination, under repository conditions. Selection of appropriate materials is therefore of paramount importance to the long-term isolation of radionuclides from the surrounding environment and the general public.

3.2.1 Engineered Barriers

A typical EBS will employ a combination of natural and man-made materials chosen to contain the particular waste stream and prevent or limit the migration of radionuclides away from the GDF.

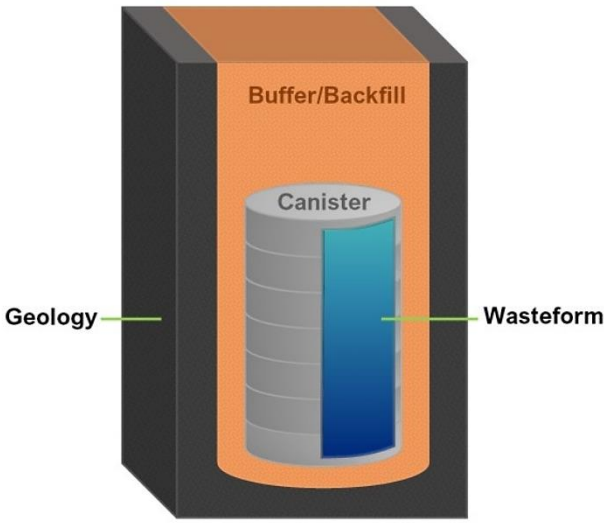


Figure 3.1: Example of a generic engineered barrier system (EBS) [133].

Principally an EBS is be made up of three generic engineered barrier layers, as displayed in Figure 3.1: a wasteform (man-made), wasteform container/canister (man-made) and a layer of buffer or backfill materials (natural or man-made) [132], [134]. This definition is generally accepted internationally, though some programmes differ in what they deem to be "barriers", for example the US Waste Isolation Pilot Plant (WIPP) project does not consider the waste disposal container an engineered barrier when conducting performances assessments, whilst the Japanese disposal programme does not account for backfill and seal materials as part of the EBS.

The wasteform typically comprises the waste stream, which has been immobilised or encapsulated in a chemically stable, robust matrix as described in 2.2.1.3. The choice of material utilised as the wasteform matrix will depend on the chemical, thermal, physical, and radiological properties of the waste for disposal, such that interactions detrimental to the long-term isolation of harmful radionuclides are minimised. Waste conditioning and packaging tends to occur directly in the final disposal container or a container which will be placed into a final disposal container. What constitutes a wasteform differs per a nations waste management strategy e.g. programmes that consider SNF as radioactive waste will be dealing with a different "wasteform" to the solid HLW or ILW considered for disposal in the UK's GDF.

The disposal container is the vessel in which the wasteform will be disposed in, within the GDF. It can comprise part of the package for waste transportation and further overpacks. Containers are often made of corrosion resistant materials, or with a corrosion tolerance, to ensure they remain intact far beyond the point of disposal. This is necessary due to the time frames and variable environmental conditions experienced from transport through to final disposal. Container material and design features will be dictated by the characteristics of the waste, wasteform matrix, buffer or backfill proposed, and specifications set out as part of future Waste Acceptance Criteria (WAC). To ensure safe handling, storage and disposal, WAC will be set out so that waste packages arrive to the GDF site in a passively safe state for disposal without further packaging or processing.

Buffer or backfill materials will be employed to permanently occupy the void space generated by the excavation of drifts and tunnels for disposal and emplacement in the GDF [133]. The nature of the backfill selected, and the form it takes will depend on the characteristics of the waste package and geological setting, and may be deposited in liquid, or solid pellet, block, or crystal form. It may be chosen simply as a means of reducing void space, or also as a means of controlling the local hydrochemistry [132].

Materials for structural support or lining, as utilised in near-surface disposal, may also be required, though these will be site and design specific.

As alluded, the choice of materials depends upon on a number of factors which will be critical to the isolation of radionuclides, including: the geological setting; interactions between the geology and EBS materials; radioactive waste heat generation; the susceptibility of materials to be damaged or degraded by exposure to ionising radiation; the susceptibility of materials to degradation through corrosion; the susceptibility of materials to degradation from microbial activity; and the potential of materials to generate gasses as a result of irradiation, corrosion or microbial activity [75]. The use of appropriate engineered barriers is critical to a GDFs ability to contain radionuclides and maintain long term nuclear safety; it is therefore essential to be able to predict how each material will behave under GDF conditions. The geology for the UK's GDF has yet to be determined, and current policy indicates a preference for a single GDF, but does not rule out a multiple site approach. Therefore a range of engineered barrier materials have been identified and considered in a number of UK and internationally developed generic designs (illustrative concepts are summarised in Figure 3.2) to address this uncertainty [119], [135].

Host rock	Illustrative Geological Disposal Concept Examples[d]	
	ILW/LLW	HLW/SF
Higher strength rocks[a]	UK ILW/LLW Concept *(NDA, UK)*	KBS-3V Concept *(SKB, Sweden)*
Lower strength sedimentary rock[b]	Opalinus Clay Concept *(Nagra, Switzerland)*	Opalinus Clay Concept *(Nagra, Switzerland)*
Evaporites[c]	WIPP Bedded Salt Concept *(US-DOE, USA)*	Gorleben Salt Dome Concept *(DBE-Technology, Germany)*

Notes

a. Higher strength rocks – the UK ILW/LLW concept and KBS-3V concept for spent fuel were selected due to availability of information on these concepts for the UK context.

b. Lower strength sedimentary rocks – the Opalinus Clay concept for disposal of long-lived ILW, HLW and spent fuel was selected because a recent OECD Nuclear Energy Agency review regarded the Nagra (Switzerland) assessment of the concept as state of the art with respect to the level of knowledge available. However, it should be noted that there is similarly extensive information available for a concept that has been developed for implementation in Callovo-Oxfordian Clay by Andra (France), and which has also been accorded strong endorsement from international peer review. Although we will use the Opalinus Clay concept as the basis of the illustrative example, we will also draw on information from the Andra programme. In addition, we will draw on information from the Belgian super container concept, based on disposal of HLW and spent fuel in Boom Clay.

c. Evaporites – the concept for the disposal of transuranic wastes (TRU) (long-lived ILW) in a bedded salt host rock at the Waste Isolation Pilot Plant (WIPP) in New Mexico was selected because of the wealth of information available from this United States Environmental Protection Agency (EPA) certified, and operating facility. The concept for disposal of HLW and spent fuel in a salt dome host rock developed by DBE Technology (Germany) was selected due to the level of concept information available.

d. For planning purposes the illustrative concept for depleted, natural and low enriched uranium is assumed to be same as for ILW/LLW and for plutonium and highly enriched uranium is assumed to the same as for HLW/SF.

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Figure 3.2: GDF Concepts considered "illustrative" in the UK's GDF development process [119].

3.3 Engineered Barrier Properties

As the location and geological setting for the UK GDF is as of yet undecided, the design specific safety functions required by the engineered barriers have yet to be fully determined [136]. Nonetheless HLW, ILW and LLW wasteforms have been conditioned and packaged awaiting

final disposal in the GDF. In the absence of a site-specific safety case, waste package production is controlled through the ONR's requirements for passively safe interim storage, and the delivery body's (Radioactive Waste Management Ltd, now Nuclear Waste Services (NWS)) Letter of Compliance (LoC) process. These provide waste producers confidence that they will produce HAW wasteforms which are compatible with NWS' waste package specification (WPS) (which through NWS' disposability assessment process provide NWS' best estimate of any future WAC) [136].

3.3.1 Radioactive Wasteforms

As illustrated by Table 3.1, the diverse nature and longevity over which radioactive waste has been produced in the UK means that a range of materials have been considered or utilised to immobilise, encapsulate, or stabilise HAW prior to storage or disposal. A brief overview of those materials primarily utilised in the UK's radioactive waste management is provided herein.

Table 3.1: The variety of wasteform materials utilised or considered for UK waste conditioning and disposal.

Waste Stream	Wasteform Matrix	Notes
HLW	Butex glass	First fuel reprocessing at Sellafield (1952-1964), utilising di-butyl carbitol extraction process.
HLW	Magnox glass Blend Glass	Sodium borosilicate containing; often high in magnesium.
ILW	Cement	Typically Ordinary Portland Cement (OPC) with one of: (1) Blast Furnace Slag (BFS) or (2) Pulverised Fuel Ash (PFA).
ILW	Polymer encapsulants	Including epoxy resin (used in UK) bitumen (used internationally; not UK), and urea formaldehyde (used internationally; not UK).
ILW & Plutonium Residues	Glass, ceramic or glass-ceramic	High temperature processes are being considered for the immobilisation of some ILW and Pu residues in the UK.
Oxide spent fuels, LLW graphite, neutron activated ILW & DNLEU	Waste without encapsulant/immobiliser, including clad material	Spent fuel not classified as waste for geological disposal in the UK as of 2021.
Post-operational clean-out (POCO) waste	POCO Glass	Management strategy in development.

3.3.1.1 Vitrified High Level Waste

Radioactive fission products arising from spent fuel reprocessing are generally immobilised in borosilicate glass to form a very stable, HLW wasteform by vitrification as described in 2.2.1.3. Borosilicate glass is utilised because of its good performance in relation to irradiation tolerance, chemical durability, thermal stability, immobilisation of a range of elements, low dissolution rates, and high expected lifetime (natural analogues ∼300 million years) [41], [47], [137]. The UK's adoption of multiple reactor types means the inventory of spent fuel that has been reprocessed largely comprises Magnox and advanced gas-cooled reactor (AGR) fuels. As such two forms of vitrified HLW product dominate the inventory of processed and packaged HLWs, "Magnox" and "Blend" glasses. Both combine the highly active liquor (HAL) from reprocessing with sodium borosilicate frit to produce chemically stable, glassy wasteforms, containing various quantities of magnesium and aluminium and a waste loading of 18-25 %. In the case of Blend glasses, liquors from both Magnox and AGR fuel reprocessing are combined, typically in a 25:75 ratio, with glass frit.

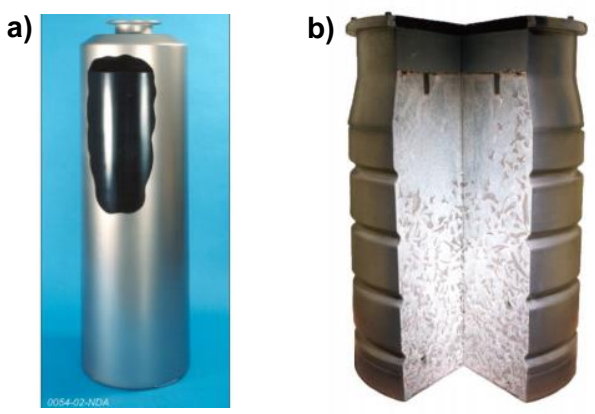


Figure 3.3: Examples of UK wasteform materials a) Vitrified HLW contained within a 309 stainless steel canister b) Cementitious ILW contained within 316L stainless steel canister [138].

3.3.1.2 Encapsulated Intermediate Level Waste

Intermediate level radioactive waste arises from a variety of fuel cycle waste streams with far lower inherent activity and heat generation than high level waste. As such encapsulation was regarded the best approach for these waste streams in the UK. Cements have been utilised to encapsulate the majority of the UK's ILW to date, via the processes described in 2.2.1.3, whilst polymeric alternatives such as epoxy resins, and bitumen and polyethylene have been considered internationally. Cements exhibit favourable properties such as irradiation tolerance, low permeability (aqueous and gas), sorption, promotion of alkaline conditions, reducing radionuclide solubility, and compressive strength all of which contribute to a wasteform which is passively safe, and which maintains physical and chemical integrity and stability for a significant period of time [139].

3.3.1.3 Spent Nuclear Fuel and Cladding

In countries that adopt a once-through fuel cycle, spent nuclear fuel (SNF) is defined as a radioactive waste, for disposal in a GDF/Deep Geological Repository (DGR). In this instance, the wasteform is not made up of highly active materials and a matrix for encapsulation, immobilisation, or isolation to form a homogenous wasteform. SNF will either be disposed of in its existing fuel assembly geometry (including cladding and structural components), or removed from its assembly and placed in disposal containers to reduce volume [140]. The UK SNF inventory primarily comprises advanced gas-cooled reactor (AGR) and pressurised water reactor (PWR) fuels.

SNF pellets will provide the first physical barrier to the release of radionuclides. SNF will be exposed to incoming groundwater and pellets will begin to release radionuclides. This occurs in two distinct phases, "instant release" and longer-term oxide dissolution. The small portion of radionuclides released instantaneously, the “instant release fraction” (IRF) will contain volatile species such as caesium-135 and iodine-129 and is seen to increase with extended fuel burn up

[41]. The retention of radionuclides in spent oxide fuel relies on the dissolution properties of the UO_2 matrix, as the majority of fission products and actinides reside within UO_2 grains. Redox conditions within a GDF are expected to be highly reducing, thus much of the uranium present sits in a lower oxidative state (U(IV)), where solubility is significantly lower than under oxidising conditions. This acts as the limiting step in the dissolution rate of UO_2 fuel and the main mechanism in the retention of radionuclides within the SNF.

SNF cladding provides the second physical barrier to radionuclide release, with Zircaloy or stainless steel utilised for the cladding of nuclear fuels. Stainless steel in particular is utilised for many of the same reasons it has been used as a disposal container material, including favourable corrosion performance at the high temperatures experienced in reactors. Cladding will physically surround radionuclides for a sustained period of time, including where SNF continues to generate a significant thermal output. Post-closure irradiation of cladding materials has not been well established in the literature, whilst it is also unclear whether the generation of further activation products such as carbon-14, nickel-59, and zirconium-93 will occur under repository conditions, highlighting an area for potential future work.

The UK has not yet declared SNF as a waste for disposal within the GDF specifically, though this does not preclude a future decisions for the GDF to host the UK's legacy SNF inventory.

3.3.2 Radioactive Waste Containers

As illustrated by Table 3.2, there are an array of materials that have been proposed or utilised in the UK for the manufacture of disposal containers for HAW. As described in 2.2.1.3, the conditioning of intermediate-level waste occurs directly in the intended container for disposal, as such the materials proposed are unlikely to change without adverse cause. However, HLW is vitrified in stainless steel containers which are not intended as "disposal containers", and will require a further overpack prior to disposal. As such many materials for the disposal of high-level waste and, if required, spent nuclear fuel, are being considered, the choice of which

will be dictated by the geological setting and compatibility with other engineered barriers.

Table 3.2: Materials identified as suitable candidates for the disposal of UK radioactive waste streams.

Waste Stream	Candidate Container Materials (UK)
ILW	Stainless Steel
	Concrete
	Ductile Cast Iron
HLW/SNF	Copper (+ Insert)
	Stainless Steel
	Titanium
	Nickel alloys
	Carbon Steel

3.3.2.1 Stainless Steel ILW Disposal Container

Stainless steel is used for cemented ILW containers because of its excellent corrosion resistance and high yield strength. In the UK, 316 L stainless steel has been utilised for the packaging of a large proportion of its ILW, as well as the 304 L grade. The 316 L grade of stainless steel is a molybdenum bearing austenitic stainless steel, with high proportions of nickel and molybdenum. Austenitic stainless steels characteristically contain 16–25 % chromium. Chromium and equivalents such as molybdenum contribute to an improved resistance to localised corrosion, via a passive, stable chromium oxide/hydroxide surface layer ($Cr(OH)_3/Cr_2O_3$). This is critical in inhibiting corrosion and reducing the effectiveness of microbes at the container surface. The low carbon content negates carbide precipitation and sensitisation, which can deplete chromium and reduce resistance to intergranular corrosion. As many passive stainless steels are nobler than most anticipated waste metals, galvonic corrosion of the waste metals (rather than the disposal container) is typically preferential [141].

Waste producers have developed multiple container drum and box designs, tailored to the

physical state of the ILW being conditioned, the shielding requirements necessary for safe transport, handling and disposal of the waste. The most frequently employed is the unshielded 500 L drum which has been used to package wastes including heterogeneous solid wastes and mixed "soft" wastes at many sites across the UK. Stainless steel has also been utilised in the storage of low-heat generating waste (LHGW) at the "Miscellaneous Beta Gamma Waste Store" (MBGWS), which is displayed along with examples of other unshielded stainless-steel ILW disposal containers in Figure 3.4.



Figure 3.4: Examples of variant standard unshielded stainless-steel storage and/or disposal container designs [142].

3.3.2.2 Concrete ILW Disposal Container

Concrete boxes and drums have been proposed for the packaging of a range of operational wastes including de-watered sludges, ion exchange resins, filters and heterogeneous solid waste. They inherently provide radiation shielding, meaning additional shielding during handling, transport and storage is not necessary, though it can still be incorporated where required [39], [142]. Concrete is readily available, well understood and provides favourable mechanical properties, as well as radiation shielding, which is why several international programmes have utilised concrete as an overpack for primary waste packaging containers. It is also envisaged that the slow dissolution of concrete containers may contribute to the chemical conditioning of the local

environment, such that radionuclide solubility and migration is limited, and the gas permeability of concrete should reduce the likelihood of internal pressurisation.

The designs proposed for UK wastes are generally manufactured to be significantly thicker than stainless-steel containers (typically on the order of 150-240 mm), which may provide challenges in terms of weight and size, and inhibit the frequency with which this design is employed [142].

3.3.2.3 Ductile Cast Iron ILW Disposal Container

Also considered for the disposal of ILW in the UK are containers made from cast iron. Multiple "robust" cast iron designs have been established (see Figure 3.5) [142]. Cast iron is considered as a thick-walled alternative to stainless steel, due to its inherent mechanical strength, and has been employed in several international programmes, including Germany, Switzerland and Canada, primarily for radioactive waste storage [108], [143]. Cast iron typically contains 2-5 % carbon alloy, with a similar matrix composition to steels, taking the form of graphite in many grades of cast iron. Graphitic grades are of most interest to disposal container design, particularly ductile cast iron [142]. The evolution of cast iron is well understood and makes the corrosion behaviour easier to predict, providing a basis for predicting durability under GDF conditions. However, some issues remain over the potential brittleness of cast iron.

Cast iron containers would have to be constructed with a thickness that provides a corrosion tolerance suitable to demonstrate sufficient safety ($\sim$160 mm), and they may also require an outer surface coating of epoxy, polymer-based paint which can help preserve their functionality [144].



Figure 3.5: Variant cast iron shielded disposal container designs [44].

3.3.2.4 Stainless Steel HLW Vitrification Container

HLW is vitrified in stainless steel containers, as described in 2.2.1.3. According to NWS' (then RWM Ltd) illustrative GDF designs, the vitrification container will not be considered a disposal container, instead it will be placed within a corrosion resistant overpack or container prior to final disposal [119]. Nonetheless it provides two valuable functions, as a container for the molten glass product during vitrification, and as a physical engineered barrier which contains radionuclides and protects the HLW wasteform from groundwater dissolution. The canister material used for the UK's vitrified HLW is 309 grade stainless steel. Grade 309 is high in chromium and nickel to give increased corrosion (oxidation) resistance at the high temperatures experienced during HLW pouring, vitrification and storage.

3.3.2.5 Copper SNF Disposal Container

Disposal containers made of copper are being considered and readily utilised in multiple national radioactive waste programmes globally, including those in Sweden, Finland, Canada, and Switzerland, for the disposal of high-level waste or spent nuclear fuel [145]. Copper has been selected principally because of its resistance to microbes and corrosion, irradiation tolerance, thermodynamic stability, and its resistance to stress corrosion cracking [134].

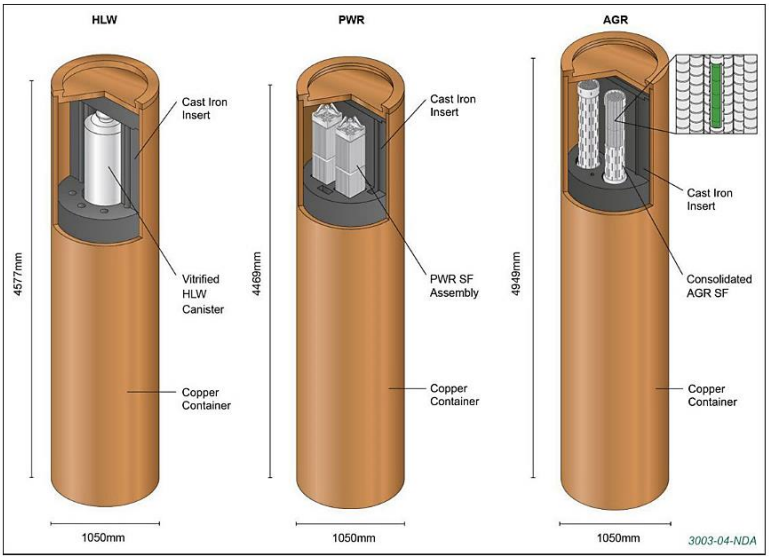


Figure 3.6: Conceptual design of a disposal container for HLW and spent fuel made of copper [41].

Copper concepts such as SKB's KBS-3 container design, adopt a dual shell approach, combining moderately thick, ductile copper outer shell (∼50 mm) with a structural insert to provide the mechanical strength required under repository conditions. In the UK, conceptual designs have been developed for HLW/SNF disposal containers, one of which adopts a similar approach to the KBS-3, as displayed in Figure 3.6. The so-called "Variant 1" design utilises a copper outer with a cast iron insert, which could accommodate multiple HLW vitrification canisters, PWR fuel assemblies or consolidated AGR fuel bundles. This design has been proposed for disposal in a high strength rock (HSR) geological setting in the UK.

3.3.2.6 Carbon Steel HLW Disposal Container

The proposed alternative to the copper "Variant 1" concept for the disposal of HLW/SNF is a single-shell, carbon steel container based on the containers developed as part of the Swiss waste management programme [146]. Carbon steel is being considered in the UK, as well as the schemes in Belgium, France, Japan and Switzerland, due to its mechanical strength and the well-established understanding of its corrosion properties in a number of geological environments.

It is also easier, cheaper and less resource intensive than copper and may promote reducing chemical conditions that could inhibit the solubility of some radionuclides. Some concerns remain over the generation of hydrogen gas as the container corrodes, which could disrupt the integrity of surrounding barriers [147].

The "Variant 2" concept utilises a 120 mm thick (compared to the 50 mm thickness of the Variant 1) cast iron single shell with the same external dimensions as the copper variant. Presently this design is envisaged for disposal in a lower strength sedimentary rock (LSSR) or evaporite environment.

3.3.3 Buffer and Backfill Materials

Materials selected for the backfilling of the GDF's galleries, disposal tunnels, access tunnels, drifts and/or shafts will be influenced by the facility's design, waste designated for disposal and the geological setting in which it's placed. This will dictate to what extent it is chosen simply to occupy void space within the repository, or whether it's selected to influence the local chemical environment. Table 3.3 contains three favourable candidates for backfilling and/or buffering the UK's GDF and the geological setting(s) in which they're considered viable.

Table 3.3: Materials identified as suitable candidates for the backfilling of UK GDF.

Backfill Material	Geological Setting of Interest
Bentonite	HSR, LSSR
Cement	HSR
Crushed Rock Salt	Evaporite

3.3.3.1 Buffer/Backfill in High Strength and Lower Strength Sedimentary Rocks

Bentonite

In many EBSs, bentonite plays an important role to backfill void space and buffer the local chemical environment. Bentonite is a natural material that offers good compatibility with HSR and LSSR environments, which exhibits capabilities as a physical and chemical barrier to radionuclide release from HAW. Bentonite is employed as a buffer/backfill material as it offers low hydraulic conductivity, self-sealing and swelling, which will slow the movement of groundwater into the near field, and of radionuclides out of the GDF [65], [119], [135]. The large proportion of montmorillonite contained within bentonite acts as a swelling agent, to close any residual space in the repository upon saturation, restricting groundwater flow to diffusion, and also facilitates ion exchange with the constituents of groundwater, including some important radionuclides.

Bentonite can condition local porewater chemistry such that it offers a low redox potential, reducing conditions and a moderately high pH, which decreases the solubility of certain radionuclides, and ensures aggressive species such as sulphides and chlorides are not present in significant quantities. It may be deposited in the repository in multiple forms, as pellets to surround the disposal container or in block/plinth form on which a disposal container may rest, as in Figure 3.7, depending on repository design.

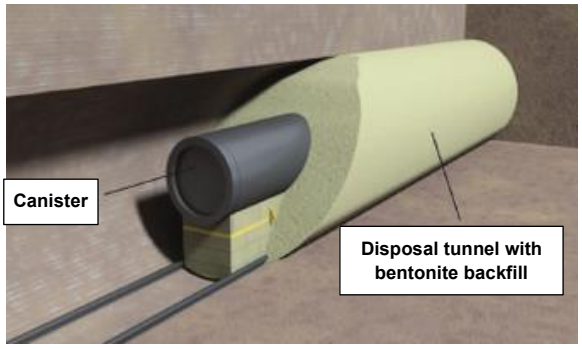


Figure 3.7: Bentonite emplaced as in the Swiss Opalinus Clay (LSSR) disposal concept in both pellet and plinth [65].

Cement

Cementitious backfills have been identified as a suitable material to act as a chemical and physical barrier to radionuclide release and groundwater ingress, particularly for the disposal of ILW [132]. Cement is favourable as a backfill due to its high pH and high permeability and porosity (relative to materials utilised for tunnel linings). Cement provides significant chemical containment through a combination of processes which condition the near field to inhibit radionuclide release from waste packages [148], [149]. The groundwater dissolution of alkali metal and calcium hydroxides in the cement can establish alkaline conditions and restrict the solubility of radionuclides in groundwater, whilst those in solution may still be removed from groundwater through precipitation, co-precipitation, or sorption to the cementitious backfill [50]. To minimise the potential effects of the hyperalkaline conditions produced during leaching, "low pH" cements (pH $\leq$ 11) have been developed and demonstrated through full scale tests [150].

In the UK, NIREX developed a high pH, high porosity backfill appropriate for its reference design for a GDF located in a HSR environment, the composition of which is summarised in Table 3.4 [148], [149], [151], [152]. So-called "NIREX Reference Vault Backfill" (NRVB) was designed to meet safety objectives which allowed for suitable high volumes to be deposited with

minimal bleeding (the presence of excess standing water produced from the hydration of the cement).

Table 3.4: Composition of NIREX reference Vault Backfill (NRVB) [148].

Component	Mass (per kg) %
Ordinary Portland Cement	450
Fine Limestone Aggregate	495
Hydrated Lime Aggregate	170
Water	615

Cementitious backfills are already widely utilised in underground engineering and are most compatible with disposal in high strength and lower strength sedimentary rock environments. Utilising cements in an evaporite environment may lead to chloride contamination and reinforcement corrosion, inducing the breakdown of the barrier over much shorter timeframes than in the HSR/LSSR environments [153].

3.3.3.2 Backfill in Evaporites

A GDF in an evaporite environment will likely be backfilled with a form of crushed evaporite such as rock salt. Over time at repository temperatures, it can homogenise with its surroundings and assume the properties of the geological environment, exhibiting low porosity, low permeability, and creep [154]. The compaction of crushed rock salt back fill leads to the effective sealing of an evaporite GDF, preventing groundwater flow to the waste containing region, achieved over a relatively short timescale [132].

In undisturbed conditions there is no recognised mechanism suggesting bulk dissolution of crushed rock salt backfill will occur, due to the intrinsic aridity of the surrounding geology. A number of brine pockets will be present in the host evaporite, which have the potential to migrate around the repository, but being highly saline are not expected to be able to dissolve significant quantities of the backfill. As such the use of crushed rock salt as a backfill is expected

to isolate waste indefinitely.

3.4 Analysis and Key Points of Importance to the Regulation of a GDF

The regulators of a GDF are not responsible for the site selection process, or in decision making regarding EBS material choices for the GDF. They will however provide oversight across aspects of EBS material choice, in particular the impact of these choices on nuclear safety and environmental protection.

As part of their obligations under both nuclear safety and environmental protection regulation, the licensee will need to submit safety documentation to demonstrate the safety of the GDF including the performance of the EBS materials chosen. To meet environmental legislation, the licensee will need to demonstrate that the best available techniques have been employed. The nuclear safety regulator, the Office for Nuclear Regulation (ONR), will need to be confident in the safety arguments presented for the materials utilised in the design, and the safety case will need to show that the engineered barriers, if implemented correctly, will provide the required level of protection for workers and the public during the construction, operation and post-closure periods of the GDF lifecycle. The Environment Agency, as the regulator for environmental protection, will need to be assured that the materials selected are compatible with the surrounding natural environment and that the EBS will deliver its claimed functions (as per an environmental safety case) in order to protect people and the environment following the closure of the GDF.

Should the design and material choices be substantially justified, regulators may still require assurance over material quality and the emplacement of the engineered barriers in order to be assured that the design intent will be delivered. The dutyholder may need to demonstrate that contractors have implemented sufficient quality control over the manufacturing, processing, packaging, storage, and transport of materials utilised in the EBS. This would provide confidence

that the GDF would meet the design safety requirements set out in the relevant safety cases and provide the levels of nuclear safety and environmental protection required of the dutyholder.

3.5 Areas for Further Research

As the site for the UK's geological disposal facility is yet to be established, it is difficult to identify specific aspects of future research that will be required in order to substantiate the safety of the EBS required to meet the GDF safety cases. Nonetheless, it would be prudent for NWS to focus research on:

- the performance of engineered barrier systems suitable for the disposal of both high and low heat generating wastes, which employ clays or cements as backfills;
- obtaining a better understanding of the direct disposal of AGR SNF (as much more focus has been given to LWR SNF);
- the dissolution of cementitious wasteforms, as more emphasis at present is placed on the performance of the surrounding EBS;
- the impact of material choices on gas generation and management in disposal areas;
- the interactions between EBS materials, and between the EBS and the geological setting, particularly in an evaporite setting where less literature focus has been placed;
- the effect of irradiation on EBS materials, including SNF cladding materials;
- the degradation of the 309 stainless steel HLW vitrification containers under repository conditions;
- modelling to support the development of EBS material choices and their performance under repository conditions, including total system modelling of radionuclide release from design concepts utilising specific EBS materials.

RWM's (now NWS') comprehensive Science and Technology Plan addresses the need for research in a number of areas including the delivery of suitable GDF backfill materials for LHGW and HHGW, security of supply for EBS materials and developing practicable emplacement options for EBS materials [155].

The foundations of much of the technical and modelling work NWS will undertake to identify suitable EBS materials can be performed generically, and these methodologies adapted to be site specific once the final site for the GDF has been selected and sufficiently characterised. It is essential that NWS build the capability to deliver the required EBS research which will be crucial in demonstrating the levels of safety outlined in the GDF safety cases.

The components of the engineered barrier system, independently and collectively, will be required to perform a number of important safety functions, and if properly designed and implemented will delay the release of radionuclides from a GDF. In Chapter 4, a high level overview of a number of performance characteristics for multiple candidate EBS materials is provided.

Chapter 4

Performance Expectations of Engineered Barriers

4.1 Introduction

Chapter 3 provided a brief overview of a number of barrier materials which may be employed as part of an engineered barrier system for a UK GDF. The combination of engineered barriers selected will depend on the geological setting of the site selected, the composition of waste inventory for disposal and the potential interactions between EBS materials.

In Chapter 4 the important role each generic engineered barrier will play in the long-term isolation of HAW from the biosphere is highlighted, and the performance of candidate materials examined. The information contained in Chapters 3 and 4 have been peer-reviewed and published as a review paper based on the role and performance of engineered barriers [133].

4.1.1 Important Role of Engineered Barriers

The detailed safety functions and safety measures associated with the wasteforms, disposal containers and backfill materials utilised as engineered barriers in the GDF will be developed when the site for the GDF has been selected and the geological setting is better understood. Irrespective of site-specific factors, there are a number of important roles each generic engineered barrier will be expected to perform, as outlined herein.

4.1.1.1 Wasteform

Wasteform materials for the UK GDF are (at present) considered the matrix within which radioactive materials are encapsulated i.e. cement for ILW, or immobilised i.e. glass utilised to vitrified HLW, or the SNF pellets which retain radionuclides once removed from a reactor. The primary function of the wasteform is to provide the first barrier to radionuclide migration. [101]. The wasteform provides physical and/or chemical containment of the radionuclides to initially prevent and, over time, restrict their release [44]. As well as being the first barrier to the outflow of radionuclides, the wasteform is required to co-exist alongside other EBS materials without deleterious effects. Wasteforms are designed to reside in a physical and chemical state that promotes passive safety when contained by the conditioned waste storage and/or disposal container. Once the backfill/buffer materials and disposal container have been breached by groundwater, the wasteform acts as the final line of defence in the retention of radionuclides. The future disposal of SNF (should it be declared radioactive waste for the GDF) marks an exception to the traditional idea of a "wasteform", being that it constitutes multiple, distinct components (cladding and SNF pellet).

The generic Disposal System Specification places onus a wasteform to provide a stable, low-solubility matrix limiting the release of radionuclides. Retention of radionuclides ultimately depends upon factors such as the wasteforms resistance to leaching, chemical stability, radiation durability and physical robustness. UK HLW is immobilised in chemically stable borosilicate glass as

discussed in Chapter 2 (Section 2.2.1.3) and Chapter 3 (Section 3.3.1.1), and UK ILW generally encapsulated in cement (2.2.1.3 and 3.3.1.2).

4.1.1.2 Disposal Container

The waste package for long-term interim storage or disposal is made up of the wasteform and a storage or disposal container. The role and function of the container depends upon the wasteform being disposed of. A number of generic safety requirements have been placed upon the waste container, though not all will apply to some disposal concepts [44]. The disposal container is primarily utilised to provide physical containment during operations and post-closure, under normal and accident conditions. Secondly, the disposal container may be expected to exhibit mechanical strength, radiation shielding, favourable thermal properties and resistance to degradation [156]. A mechanically strong disposal container would provide resistance to damage caused by internal pressurisation and loads, and ensure the required impact accident performance is met. It is important for the disposal container to exhibit good resistance to degradation for at least the length of the thermal period of the wasteform, to allow for effective decay of short-lived isotopes, maintain sub-criticality and ensure there is no early accumulation of fissile materials from more than a single waste package in post-closure.

A number of materials have been identified or investigated as part of the UK geological disposal programme (Section 3.2.2) [135].

4.1.1.3 Buffer and Backfill Materials

Backfill materials are utilised to fill the voids created during excavation of the GDF, between the wasteform and the walls of disposal vaults or tunnels. For HSR and LSSR environments, materials such as bentonite, NRVB and concrete are proposed as chemically compatible backfills/buffer materials (see 3.2.3). Backfill materials are chosen for their structural behaviour and low permeability, to restrict groundwater flow and radionuclide release. The "self-healing" of LSSR

and evaporites can be effectively mimicked by a number of backfill materials. Clays that swell and eradicate fractures have been investigated as backfill materials in HSR/LSSR, and crushed rock salt as a void filler in arid evaporite environments.

Buffer materials differ as they also provide stability and protection to the waste package through control of local hydrochemistry. Buffer materials are used to maintain a favourable pH in the local environment, invariably promoting alkaline conditions. This may inhibit microbial activity at the disposal container surface, reduce the potential for corrosion of the container and restrict the mobility of radionuclides once the disposal container has been breached.

4.1.2 Performance Expectations of Engineered Barriers

As referred to previously, the GDF's engineered barrier materials will be selected to perform specific functions to meet the requirements of the waste and geological setting and to ensure compatibility with other barriers. A such, an understanding of the performance of these barriers is critical for the development of both the operational and post-closure safety cases.

4.1.2.1 Wasteform Performance

Vitrified High-Level Waste

HLW glass incorporates a significant concentration of fission products and higher actinides, which readily undergo radioactive decay. The radiation field generated can induce radiation damage in the vitrified glass matrices, transmutation of decaying radionuclides and the generation of helium atoms. Beta radiation from the decay of short-lived radionuclides dominates the radiation field for several hundred years, though studies simulating this decay have demonstrated no appreciable effect on the leaching behaviour of simulant glasses [41]. Beta particle-atomic nuclei collisions produce very few direct atomic displacements and the expected ionisation doses of up to 10^{10} Gy are not likely to reach the threshold at which substantial decomposition,

bubble formation or phase separation will occur. As such, beta decay is not expected to hinder wasteform performance significantly [157], [158].

Alpha radiation however can result in displacement rates three orders of magnitude greater than beta decay, and affect a number of the wasteform properties including its density, Young's modulus and hardness [158], [159]. The volume of the glass wasteform has been observed to fluctuate with the number of alpha decays per gram ($\alpha.g^{-1}$), up to 1 vol% at 10^{18} $\alpha.g^{-1}$. These volume changes could cause increased strain on the surrounding stainless steel container. However, these changes have been observed to cease in the region of 2–4 $\times$ 10^{18} $\alpha.g^{-1}$. For UK vitrified HLW, it will take thousands of years of alpha decay to result in $\sim$ 10^{19} $\alpha.g^{-1}$. At this rate of alpha decay, simulant glasses have been observed to remain microscopically homogeneous, with no adverse impact on glass integrity, or an increase in phase separation, crystallisation or bubble formation. Elevated temperatures due to radiolytic heating and radioactive decay may lead to microstructural changes in glasses during storage and early disposal, including de-vitrification of HLW [44].

Once other engineered barriers have been compromised, the vitrified glass matrix will be exposed to groundwater, which may be contaminated with other degrading media. Estimates of the dissolution or "leaching" behaviour of UK HLW glasses have been generated by a number of studies [41], [137]. At elevated temperatures, dissolution rates obtained from the normalised mass loss of boron in simulant glasses indicated dissolution on the order of 9.6 $\times$ 10^{-4} $g.m^{-2}.day^{-1}$ [137]. This was used to estimate the long-term leach rates of Magnox Waste Simulant (MW) glass under repository conditions. A rate of 4 $\times$ 10^{-5} $g.m^{-2}.day^{-1}$, corresponding to a glass package dissolution rate of $\sim$ 0.22 $\mu m.yr^{-1}$; assuming uniform dissolution, this might indicate an expected wasteform lifetime in the region of 10^5–10^6 years (to complete dissolution) [47]. The dissolution rate could be higher in the presence of hyperalkaline conditions, and may need to be considered for the co-location of vitrified HLW and cemented ILW [48].

In geological settings where advection dominates groundwater movement (i.e. HSRs), low dissolution rates will be critical in slowing the release of significant quantities of radionuclides

before sufficient decay has occurred. The leaching of simulant Magnox glasses has shown only minor variances in dissolution when varying groundwater composition (HSR, LSSR and evaporite); as the UK is yet to conclude its siting process for the GDF, it's important that the selected geology for the GDF will not significantly affect the corrosion of vitrified HLW. [160].

The formation of yellow phase, made up of ∼80% soluble alkali molybdates and ∼20% insoluble alkaline earth and rare earth molybdates, during the vitrification process on or near vitrified wasteform surfaces is an issue which could increase the initial instant release fraction (IRF) of some critical radionuclides [161]. This phase can act as a host to many surface species, including long-lived FPs such as technetium-99 and caesium-135 and potentially actinides such as americium-241, enabling an increased proportion of radionuclides to be released earlier. The rate of yellow phase production is influenced by calcination conditions, vitrification temperatures and the degree of mixing during melting, as well as the molybdenum content of the glass [34]. When quantified in UK waste vitrification products (WVP) however it was concluded its formation contributed to only ∼5 g per 190 kg pour, and should not pose a major issue to wasteform integrity/radionuclide release.

This demonstrates the robustness of vitrified HLW, and provides some confidence in its long-term performance. There remain some uncertainties surrounding the potential effects of the hyperalkaline conditions established by certain backfill materials on glass alteration and dissolution. As such further work is required to better understand dissolution under these conditions, and in the likelihood of alkaline plume migration in co-located repositories [48].

Cementitious Intermediate-Level Waste

Wasteform grouts have been shown to demonstrate good levels of resistance to irradiation when exposed to external gamma irradiation and internal alpha sources, displaying minimal microstructural disruption [162], [163]. Irradiation of cementitious materials can result in cracking or swelling, through radiolysis of porewater, hydrogen generation or the formation of expansive phases. However this has only been observed at exposures of greater than 9 MGy in

BFS/OPC and PFA/OPC samples. 9 MGy is equivalent to ∼90% of the expected lifetime dose for cements containing ILW; resistance up to 100 MGy is generally considered for cements not in contact with radioactive materials [164]–[166].

Typical grouts used for ILW encapsulation exhibit extremely low aqueous permeability on the order of 10^{-18} -10^{-20} m^2, corresponding to fluid flow of 10^{-12} -10^{-14} $m^3.s^{-1}$. Gas permeabilities are expected to be a couple of orders of magnitude higher [167]. This will be important in restricting the migration of mobile, aggressive ions such as sulphates (SO_4^{2-}) through the cement, which can react to form expansive products like ettringite, causing cracking and spalling of the wasteform matrix.

The chemical environment provided by cementitious wasteforms is important in restricting radionuclide release when exposed to groundwater. The groundwater mobility of many radionuclides is restricted by the formation of hydroxides in groundwater, particularly in highly alkaline conditions such as those promoted by high pH ILW grouts. Restricted solubility or mobility is crucial in environments where advective groundwater pathways are abundant.

Once contacted by groundwater, leaching and chemical processes such as chloride and sulphide attack will occur in cementitious wasteforms [168]–[170]. These can lead to the increased mobility of constituents such as caesium, strontium and plutonium (up to 9×10^{-5} $wt\%.yr^{-1}$ has been observed), and the formation of "U-phases" which form expansive products that can cause wasteform spalling and increase the surface area for dissolution/leaching [171]–[174].

Reaction of cements with carbon dioxide can lead to the generation of calcium carbonate ($CaCO_3$), through a process known as carbonation. As a result alkalinity may be reduced, with the local pH decreasing ($pH < 8.5$), which could impact on the corrosion behaviour of encapsulated metals or the disposal container and increase the solubility of some actinides in groundwater. Increases in compressive strength and a decrease in cement surface porosity have been observed due to carbonation however, and it is possible some radioactive carbon-14 may be retained in the reaction. Carbonation penetration analysis on simulant wasteforms

containing OPC/PFA found that penetration was restricted to 2–3 mm, and progressively slowed [173], [175]. By occupying surface pores with a higher molar volume than the hydroxides, the carbonate restricts the progression of CO_2 (and other species), inhibiting further local pH decreases and increasing tensile strength.

A number of aspects of cementitious ILW performance require further investigation. For example, under acidic conditions, the integrity of a cementitious wasteforms is not well understood as in alkaline conditions. Additionally, many more studies have focused on the performance of cementitious materials as a backfill, rather than its implementation as a wasteform. It has been assumed that that the dissolution of ILW wasteforms will not significantly alter overall EBS properties, therefore formal lifetime estimates for the leaching of cementitious wasteforms have not been generated. UK R&D efforts and many post-closure models place importance on the role of further engineered barriers rather than the evolution of specific ILW wasteforms [41].

Spent Nuclear Fuel

The retention of radionuclides in spent oxide fuel relies on the dissolution properties of the UO_2 matrix, with the majority of fission products and actinides residing within UO_2 grains. Redox conditions within a GDF are expected to be highly reducing, with much of the uranium present in a lower oxidative state (U(IV)), where solubility is significantly lower than under oxidising conditions. This will act as a limiting step in the dissolution rate of UO_2 fuel and the main mechanism in the retention of radionuclides within the SNF. The rate at which dissolution may occur will also be influenced by groundwater flow rate and composition, matrix cracking and increased porosity and any micro-segregation which has occurred in the spent fuel.

The dissolution of AGR and LWR fuels is reported to be similar despite the difference in the geometry of the pellets, average assembly burn-up and maximum observed pellet-cladding interface temperatures [41], [176].

Cracking and increased porosity are induced by the thermal expansion and fission gas generation associated with fuel burn up, and can increase the available surface area for spent fuel dissolution

within a GDF. Redistribution of FPs ("micro-segregation") during the fuel's operation will lead to increased local concentrations of a small fraction of elements (e.g. chlorine-36, iodine-129 and caesium-135), some of which are highly soluble and will affect the leaching behaviour of the fuel. These are volatile at fuel centreline temperatures (in-reactor) and migrate to grain boundaries or fuel-cladding gaps. Increased burn up encourages micro-segregation, increasing the IRF of certain elements. Experimental studies have demonstrated that under anoxic conditions, UO_2 dissolves at a rate of 10^{-3} –10^{-6} mol.m^{-2}.yr^{-1}, corresponding to a mass loss of 10^{-7}%.yr^{-1} [177]. Fractional mass loss has been employed to estimate SNF dissolution of LWR fuel in the Swedish disposal programme. Results indicated the entire SNF inventory would be released over a period of approximately 1 million-10 million years [177], [178].

Spent Fuel Cladding

Stainless steel was primarily selected for cladding AGR fuels because of favourable corrosion properties in high temperature CO_2. The corrosion of stainless steel in aqueous conditions are also favourable, with low general corrosion rates on the order of 0.001–0.1 μm.yr^{-1} estimated for repository conditions [179]. Assuming general corrosion to be the only mechanism for cladding corrosion, and that the cladding is intact upon disposal, a typical 300 μm thick cladding could be expected to remain intact for up to 300,000 years prior to rupture. However, localised corrosion, including pitting and stress corrosion cracking may occur under conditions where the chloride (Cl^-) concentration in groundwater is sufficiently high (>1 mg.ml^{-1}), at relatively high humidity or temperature (>60 °C) [180]. The integrity of cladding could be severely hindered under these conditions, once significant quantities of groundwater have penetrated the surrounding engineered barriers [181].

Neutron irradiation during reactor operation can induce helium generation in the stainless steel ("sensitisation"). Helium bubbles aggregate at grain boundaries within the steel, depleting it of chromium which precipitate from the cladding sub-surface and increasing susceptibility to localised corrosion [182]–[184]. Helium also impacts on the physical properties of stainless steel, marginally increasing hardness (∼10%) [185]. Sensitisation increases the likelihood of fuel

cladding perforation under aqueous/humid or saline (chloride) conditions, which could lead to earlier failure of cladding material. This phenomena is conservatively estimated to be able to increase corrosion rates by up to a factor of 10 [186].

The Zircaloy cladding used for LWR fuel exhibits good corrosion properties in water, with a general corrosion rate of 0.003–1 μm.yr^{-1} , whilst also exhibiting a low neutron capture cross section [187], [188]. Zircaloy is typically 300–500 μm thick and may therefore be expected to remain intact for up to 150,000 years under suitable conditions. Localised corrosion in Zircaloy may manifest through the breakdown of the Zircaloy's passive oxide film layer, or the absorption of hydrogen [189]. At sufficient levels of groundwater salinity and oxidising conditions, the passivation layer can break down leading to pitting corrosion. However research indicates H_2O_2 formation due to the hydrolysis of water by gamma radiation can increase the pitting corrosion resistance of Zircaloy through a thickening of the passive oxide film layer present on the Zircaloy surface [190], [191]. Hydrogen embrittlement and hydride cracking is also an issue; Zirconium can react with water to form zirconium oxide and elemental hydrogen, which can penetrate the cladding and lead to embrittlement by forming zirconium hydrides. Hydrogen is up to 100 times more soluble in zirconium at the ambient temperatures expected in the first few hundred years post-disposal, compared to reactor operation temperatures [188]. However hydrogen embrittlement and cracking are considered unlikely due to hydride reorientation and the low redox potential of incoming groundwater [188]. General corrosion is therefore expected to dominate Zircaloy degradation in the GDF.

Incident irradiation of Zircaloy during operation may affect a number of physical, mechanical and corrosion properties of Zircaloy, including inducing irradiation growth, dimensional changes under no stress, increased hardness, reduction in the creep capability of Zircaloy and corrosion resistance [192]. Irradiation can cause the formation of point defects within the cladding matrix, which may provide preferential pathways for the migration of carbon-14 to the surface for enhanced corrosion. However the relationship between corrosion rate and carbon-14 release has not been sufficiently substantiated. [193].

4.1.2.2 Disposal Container Performance

Vitrification and disposal containers primarily act to physically contain conditioned HAW in the GDF for a significant period of time, during which time the levels of radioactivity will have reduced significantly through radioactive decay. As such, the material properties which enable the physical integrity of the container to be maintained for as long as possible are a major factor in the selection of container materials.

Stainless Steel Intermediate-Level Waste Container

Stainless steel disposal containers for ILW exhibit high yield strength, typically in the region of 200–500 MPa, making them formable and weldable, which may induce high residual stresses from manufacturing. The residual stresses associated with container manufacture will be offset by the compressive strength of wasteform encapsulants (i.e. cement), which is important in geologies that exhibit creep-like behaviour and exert external pressure on the container.

Corrosion rates can vary depending upon environmental conditions such as temperature, pH and aerobicity. General corrosion rates in the region of 0.01–7.4 μm.yr^{-1} have been observed in austenitic 316 L, 500 litre containers used to dispose of cemented ILW in the UK under anaerobic, alkaline conditions. Based on this, a disposal container might be expected to fail due to corrosion as early as 3500 years, though it's suggested that long-term corrosion rate will equilibrate to values less than 0.01 μm.yr^{-1}, which would increase container lifetime to values in the region of ∼250,000 years [194]. For cemented ILW, it is expected that a cementitious backfill compatible with HSR and LSSR geological settings will be used for the UK GDF. For a GDF in an evaporite geological settings, crushed rock salt is expected be used as the back fill. This backfill will contain large proportions of chloride (Cl^-) ions which can contribute to localised corrosion through protective film passivation.

Localised corrosion mechanisms such as pitting, crevice corrosion and stress corrosion cracking (SCC) become important in aerobic conditions, in the presence of aggressive species such as chlorides or thiosulphates and at elevated temperatures [41], [141], [195]. Such conditions,

may occur during the early stages of buffer/backfill saturation, prior to the equilibration of alkaline conditions or in instances where humidity and Cl^-- level controls fail. The presence of Cl^-/thioshulphate $(S_2O_3)^{2-}$ and/or sulphide (S^{2-}) ions in increasingly acidic and/or high temperature conditions can contribute to the propagation of SCC in austenitic stainless steel. However below 60 °C and chloride concentration of 1 mg.L^{-1} in aerobic conditions, SCC is not expected to occur in 316 L [196]. Critically, irradiation is seen to have no measurable effect on the rate of localised corrosion in stainless steels [180].

Stainless Steel High-Level Waste Vitrification Container

The high nickel and chromium content of 309 stainless steel ensures general corrosion rates are low. As part of the Belgian research programme into geological disposal, 309 stainless steel was exposed to a humid clay atmosphere and exhibited a corrosion rate of 0.1 μm.yr^{-1} at 90 °C [196]. Irradiation at dose rates of 400 Gy.hr^{-1} was not seen to inflict further degradation of the waste container in direct contact with the LSSR [197]. For standard 5 mm thick vitrification containers, this would constitute a corrosion lifetime of ∼50,000 years [197]. Increased temperature under conditions relevant to evaporite geologies has seen the rate reduced to <0.05 μm.yr^{-1}. Relative to 316 L, the carbon content of 309 is significantly larger. This will impact on the formation of carbides and sensitisation during welding, to the detriment of its corrosion resistance in aqueous environments. Welds comprise chromium depleted zones that are more susceptible to intergranular corrosion, which can produce faster corrosion rates than general corrosion in the presence of aggressive ions [198]. The vitrification container will not be utilised as the lone disposal container, so an increase in localised corrosion won't hinder safety case assumptions significantly.

Copper High-Level Waste Container

Minor corrosion of copper containers can occur during the GDF pre-closure period due to the reduction of residual oxygen on the canister surface [41], [135]. Under anaerobic conditions (post-closure), copper corrosion is only possible in the presence of sulphide ions, which allow

water to act as an oxidant. Corrosion under these conditions is dictated by the rate of sulphide migration from the buffer-geology interface. General "uniform" corrosion is expected to be the dominant mechanism post-closure, as the reducing conditions maintained by the surrounding EBS won't promote localised corrosion. The corrosion resistance of copper under repository conditions has been investigated by multiple international programmes including the Prototype Repository Project (PRP), Miniature-Canister (Mini-Can) and Long Term Test of Buffer Material (LOT) test series [199], [200]. Simulant copper canisters exposed to conditions representative of a GDF in a HSR were observed for average rates of general and localised corrosion. Results are summarised in Table 4.1

[200]–[204].

Table 4.1: Copper corrosion rates from a number of international investigations.

Experiment	Variables	Corrosion rate/ µm.y^{-1}
PRP	Aerobic conditions	0.2-1.3 (recorded) $\sim$ 0.4 (estimated)
LOT	Aerobic conditions	$<$0.5
Mini-Can	Sulphate reducing microbes	0.15
Taniguchi *et al.*	Synthetic seawater Sulphide concentrations(0-0.1 M)	0.6-15

Even in non-ideal GDF conditions, such as the presence of oxidants, air or reduction of sulphates, copper corrosion did not adversely affect the performance of the container. From the corrosion rates shown in Table 4.1, the lifetime of the 50 mm thick, KBS 3V concept container, would fall in the range of 38,500 and 330,000 years. However, estimates of the performance of copper container have been called into question as the corrosion and ductility data utilised in some studies has been disputed. This led to a major research programme by SKB to substantiate the effectiveness of copper containers as an engineered barrier for the disposal of SNF in Sweden [205]–[207].

Copper utilised for SNF containers may be doped with 30–70 ppm phosphorus to increase its creep ductility and reduce the risk of strain failure, for example as a result of bentonite

swelling, which might cause copper containers fluctuate in diameter and length. SKB have also demonstrated that doses of 100 kGy result in no further significant changes to the properties or microstructure of copper, and that exposure to gamma radiation has no significant effect on corrosion, with corrosion limited to a penetration depth of ∼100 nm for this magnitude of dose [47], [48], [137]. As a result of the low inherent strength of copper, it's necessary to utilise an interior structural support to maintain the integrity of the container under external pressures [208].

4.1.2.3 Buffer and Backfill Material Performance

The choice of buffer or backfill material will be dictated by the geological setting and compatibility with other engineered barrier materials. As such what's expected of this engineered barrier will also be specific to the final GDF design, though a consideration for restricting groundwater flow is consistent in each case.

Bentonite Buffer

Upon saturation, bentonite expands, closing gaps between the bentonite and waste container, GDF gallery walls, and between bentonite blocks, pellets and/or plinths. As the gaps close a swelling pressure is generated and this reduces the fluid permeability and hydraulic conductivity of the bentonite to levels significantly low enough to allow diffusion of groundwater to dominate. Advective flow is estimated to occur at conductivities of 10^{-12} m.s^{-1}; experimental studies demonstrate values in the region of 10^{-13}-10^{-14} m.s^{-1} for a number of bentonite variants [209]–[212]. These estimated and experimental flow rates would therefore suggest that for a 1 m thick bentonite protective layer it would take between 30,000 and 3 million years for water to reach the disposal containers.

As a result, bentonite is highly impermeable (10^{-21} m^2) reducing the likelihood of advective groundwater flow. Bentonite also hinders the rate of corrosive processes; at swelling pressures of 2 MPa, bentonite eliminates microbes from the buffer-container interface, whilst this swelling

also allows for the self-sealing of potential fractures [213], [214]. As well as restricting the flow of water to the disposal container, bentonite also limits the migration of radionuclides following container failure. The cation exchange capacity (CEC) of clays is well understood and field tests for bentonite under repository conditions have shown that it is able to exchange 60–110 $cmol_c.kg^{-1}$ cations, the equivalent of 144 mol of cations per disposal borehole according to SKB [215]–[217]. Cation exchange is an important feature of bentonite, as exchanging mobile radionuclides and storing them in its pores significantly inhibits their migration. This has been noted for prevalent radionuclides like caesium and does not appear to deviate considerably due to irradiation [218], [219]. Further research is needed to better understand the performance of bentonite in the presence of ionising radiation in relation to the sorption of many other radionuclides. This is important as irradiation effects could hinder one of bentonite's beneficial attributes and increase the uncertainty of any GDF post-closure risk analysis.

Bentonite does not buffer near field pH to the same highly alkaline values (pH $\sim$ 10.0–12.0) as cementitious buffers. However the dissolution-precipitation of trace carbonates in the bentonite does condition porewater to a pH in the neutral to mildly alkaline (7.2–9.4) region, ensuring corrosion rates for container materials (e.g. copper) remain relatively low. No formal assessment of the increase in container lifetime as a result of this effect has been made, in part due to the specificity of each GDFs geology. Bentonite degradation as the GDF evolves will be dependent on the hydrochemistry of the surrounding geological environment. For example, the permeability of bentonite may be impacted by localised piping erosion, which is associated with high groundwater inflow from fractures in the host rock. This phenomenon, and the rate of saturation of the bentonite buffer, will be specific to both the choice of geology and the location of individual excavations/deposition holes within the repository.

Cementitious Backfill

The evolution of cement backfill/buffer materials such as NRVB will depend on the chemistry and flow characteristics of incoming groundwater. Hydration products present in cements, such as calcium-silicate-hydrate (C–S–H) gels and portlandite ($Ca(OH)_2$) will react with

cement porewater or groundwater to generate alkaline species such as hydroxyl ($(OH)^-$) ions that maintain solution pH to between 10.5 and 12.5 [148], [149], [220]. Should the hydroxyl concentration of porewater be maintained above 10^{-5} mol.kg^{-1}, then a pH greater than 9.0 is expected to be maintained for a period of ∼1 million years [221]. Highly alkaline conditions are favourable for the long term integrity of disposal container materials such as stainless and carbon steels [50]. Porewater hydroxyl concentration is also important in inhibiting the solubility of many key radionuclides such as plutonium(VI), thorium, americium and technetium present in HAW at high pH. Hydroxyl ions can preferentially form hydroxides with radionuclides, reducing solubility at elevated pH [50], [222]. However preferential pH buffering may be offset by sufficiently high silicon and calcium concentrations in groundwaters. High ionic concentrations of C–S–H phase components in groundwater will reduce the rate of dissolution of C–S–H and hydroxide formation, thus reducing buffering capacity [221].

Cements anticipated for backfilling generally exhibit porosity of up to 50 % meaning up to half of the cements volume is occupied by void fractions. Porous cements provide a large surface area, containing solid phases which facilitate the precipitation and sorption of radionuclides [221], [223]. These phases exhibit varying surface areas, one study demonstrating a portlandite phase exhibited a surface area of 6000 m^2.kg^{-1}, and C–S–H phases a surface area of 148,000 m^2.kg^{-1}, available for sorption. Some phases (such as C–S–H) even facilitate the sorption of both anions and cations; sorption will significantly inhibit the concentration of radionuclides migrating through the EBS. Processes such as carbonation, dissolution/precipitation of sorbing minerals and the presence or organic degradation products may however reduce the effective sorption of a cement. The high porosity of cement backfills promotes high gas permeability, which can prevent significant pressure build up behind the backfill that could lead to the development of fractures in the cement and increased permeability to groundwater flow [148], [149], [221], [224], [225]. However, carbonation of portlandite and C–S–H phases can result in the generation of secondary minerals which may "armour" any cracks within the backfill (generated by shrinkage, sulphate attack etc.), reducing permeability at the crack surface and altering the local accessibility of groundwater and gas flow. An understanding of such processes is necessary in being able to

accurately understand how cement will perform as a barrier to radionuclide release and has been a driver for significant study [221], [226].

Crushed Rock Salt

In evaporite environments, it is anticipated that tunnels and shaft seals will compact to permeabilities representative of the host rock within 200 years. Rock salt utilised in the gallery excavation as a buffer/backfill could take up 1000 years to compact to the same levels. Strain controlled compaction tests have been used in projects such as the Backfill and Material Behaviour in Underground Salt Repositories (BAMBUS II) and Residual Porosity and Permeability (REPOPERM) Phase 2, to identify the evolution of salt backfill [227], [228]. Results of the BAMBUS II in situ tests showed that crushed salt backfill, with an initial porosity of ∼35 %, when subjected to a drift closure rate of 0.5 %.yr^{-1} (over 10 years), saw a reduction in porosity of almost 10 %. Laboratory studies at varied moisture, compaction rate and humidity conducted as part of these programmes concur, with rock salt porosity reductions between 6.6 and 20 % observed [227], [228]. Compaction induced porosity and permeability of crushed rock salt makes it a good backfill material for an evaporite located GDF, as is evident in the backfilling of salt and potash mines [229]–[231].

4.2 Implications for Regulation of a GDF and Future Work

The favourable performance characteristics of some candidate EBS materials have been explored throughout Chapter 4. This demonstrated that some barrier materials may be expected to retain their physical integrity on the order of tens of thousands, or in some cases millions of years. Such periods will allow significant radioactive decay to occur prior to radionuclide release from HAW.

It will be necessary that in order to sufficiently understand and trust in the performance of materials proposed for the GDF's EBS, that site and design specific research is conducted

and presented as part of future safety submissions for the GDF. If the GDF safety arguments are critically dependent upon the performance of the engineered barriers, regulatory attention would need to focus on the evidence substantiating the performance of the engineered barrier materials. Regulators might also need to focus on more stringent quality assurance for material manufacturing and emplacement. This research will also need to feed into complex, site-specific modelling work to develop an understanding of the short- and long-term implications of EBS material choices on radionuclide release, and risk to the environment and the public.

Throughout Chapters 2-4, an understanding of the expected performance and characteristics of engineered barriers and geological settings has been developed. Chapter 5 provides a description of the work undertaken in developing and implementing a simple insight model simulating the effects of a number of sensitive parameters, originating from the EBS and/or geological setting, on the radiological risk to members of the public. This model specifically targeted the geological disposal of spent advanced gas-cooled reactor (AGR) nuclear fuel.

Chapter 5

Modelling Sensitivity Study of Radionuclide Release from Spent AGR Fuel

5.1 Introduction

Chapter 4 highlighted some of the performance expectations placed upon the engineered barrier system (EBS) for a GDF and the roles they may be designed or selected to fulfil. The work reported in Chapter 5 was conducted to begin to gain an understanding of key factors that could influence the risk to the public from the disposal of radioactive waste in a GDF. Within this work, an analysis was conducted of the factors that might influence the risks associated with the geological disposal of the UK's AGR in a GDF. Information of this nature will be important for the development of an appropriate regulatory framework, which exerts sufficient control and oversight of the risks to the public both now and in the future. Despite the UK not currently designating spent fuel of any nature (including AGR) for disposal in a future GDF, it was noted that spent AGR fuel currently represents the largest proportion of a potential waste stream with the highest associated levels of radioactivity. The inherent risk this could

pose, coupled with the relative heterogeneity of current HHGW waste streams (i.e. vitrified HLW, ILW), were motivations for modelling SNF in the sensitivity studies described herein (as opposed to waste streams already designated for disposal in the GDF). It was felt this would be useful, particularly if it could demonstrate that the highest activity waste stream did not pose significant risk to potentially exposed members of the public.

Modelling is fundamental to all aspects of science, abstracting complex systems to improve our understanding of systems and their evolution [232]. This is apt when considering the UK's implementation of the geological disposal of radioactive waste. Nuclear Waste Services (NWS), as the delivery body for the UK's GDF, will conduct safety and performance analysis when assessing the suitability of potential sites and GDF designs to understand the operational and post-closure safety of geological disposal. [62]. Such assessments will allow NWS to evaluate the behaviour of a proposed disposal system and its radiological impact on human health and the environment, through the development of models of differing complexity, ranging from higher-level insight models of GDF behaviour to site-specific total system models representing radionuclide release to the biosphere [18], [233].

This chapter provides an insight into the risks to the public, at the time of final waste emplacement and in the future, from the direct disposal of spent nuclear fuel (SNF) from the UK's advanced gas cooled reactor (AGR) programme, in a GDF located in a hypothetical LSSR geological setting (based on geological data from the Swiss programme) [234]–[236]. The analysis of the risks associated with the disposal of AGR SNF was selected because of the possibility that, following the ceasing of the UK's SNF reprocessing, AGR SNF may be disposed of in the GDF if UK policy changes. To undertake this analysis, a high-level 1-D model was developed using the probabilistic simulation software GoldSim, to evaluate, at an indicative level, the release of radionuclides from the inventory of spent AGR fuel.

The radiological risk to potentially exposed groups (PEGs) at the surface was calculated from the flux of radioactivity incident upon the biosphere once the engineered barriers have begun to to fail. Building upon this, sensitivity studies were carried out to determine if variability in

a number of GDF-specific parameters would significantly impact on the level of radiological risk posed to the public. This model employs a source term representing the radionuclides associated with the UK's spent AGR fuel inventory and assumes a specified disposal container breach time, as opposed to evaluating specific canisters and their individual failure mechanisms. Representation of individual canister characteristics would have required significantly more time and resource in the development of the model, deemed unnecessary for the purpose of this investigation. A research paper based on the contents of Chapter 5 of this thesis was peer-reviewed and published [237].

5.2 GDF Modelling Overview and Methodology

This section outlines the conceptual model and processes described in the mathematical model built in GoldSim. The mathematical implementation of these processes in the radionuclide transport module can be found in the Appendix B of the GoldSim Radionuclide Transport Module user guide [238].

5.2.1 GoldSim Software

The model was developed using GoldSim, a Monte Carlo simulation software tool which is utilised for the dynamic modelling of a host of multifaceted systems and processes, which includes the transport of contaminants and radionuclides through a complex network. It facilitates intuitive modelling through the use of object-oriented interfaces and allows for deterministic and probabilistic solutions to be sought, to accurately represent a number of inherent system variabilities. GoldSim software has been utilised by NWS' predecessor, RWM Ltd, in the development of simple and total system models representing the release of radionuclides from a number of higher activity waste streams. Models built in GoldSim can consist of a series of cell pathways between a source term (representing our SNF) and intended target/endpoint, which

are occupied by solids and groundwater, representing the different barriers, both engineered (i.e. buffer materials) or natural (i.e. the geology) [119].

5.2.2 Conceptual Model

The conceptual model makes qualitative assumptions about the design of the GDF and in doing so provides a "description in terms of the general features present and their detailed characteristics" [32], [239]. A schematic of the conceptual model built and employed for this study is outlined in Figure 5.1. Waste canisters are located in the repository at a depth of 500 m below the surface, with the canister surrounded by bentonite [240]. The host geology is assumed to be a hypothetical LSSR bed approximately 100 m thick above disposal galleries, which is based on a low permeability lithology based on Swiss Opalinus Clay [241]. Radionuclide migration towards the biosphere is assumed to be driven by diffusion of groundwater. Above the LSSR it is assumed that there is an overlying chalk layer of variable thickness of between 400-450 m. Chalk is an extensive and common lithology at these depths in a number of regions of the UK. It is present in the adopted generic designs by RWM for a GDF in LSSR [110]. Fractures are present in this region, which coupled with the low transport porosity of the chalk ensure groundwater flow is dominated by advection.

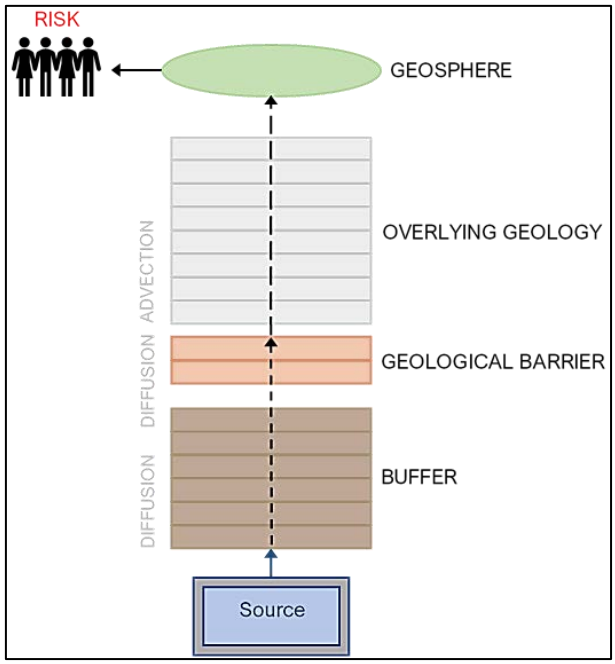


Figure 5.1: The conceptual model for the radionuclide release model built in GoldSim.

The biosphere comprises any surface or near-surface features which may act as a reception vessel for radionuclides carried by groundwater from the repository, such as fresh water sources (rivers, lakes) estuaries and the atmosphere. From this the impact on PEGs has been estimated.

5.2.3 Model Description

The GoldSim flow model utilises a simple representation of 1-D uniform flow from the spent fuel source term to the biosphere, similar to those presented in international publications based on waste management disposal and site clean-up [242], [243]. It makes a number of assumptions or simplifications compared to RWM's total system model (TSM), though the theory and equations that form the basis of this model originate from the TSM programme [244]. These assumptions include the removal of matrix diffusion in advective segments of the model, and 1-D flow being concentrated exclusively upstream, away from the source towards the biosphere, as well as omitting the effect of degradatory organic materials, which may impact on radionuclide sorption

and solubility. These simplifications were implemented to reduce the number of potential uncertainties in model development and act to conservatively ("over-estimate") estimate the flux of radionuclides released to the biosphere.

A number of parameters in the model are represented probabilistically, with values selected by distribution functions including log triangular and uniform distribution functions to better quantify the effect of parameter uncertainties on the radiological risks generated by the model. These included radionuclide solubility limits, sorption coefficients to the bentonite buffer, LSSR and overlying lithologies and physical parameters of the buffer and geosphere (i.e. dry density, porosity, transport porosity) which were derived from the RWM's 2016 Data Report [241].

Within GoldSim, an "inventory cell" is defined as the location into which exposed mass from the source is released. This is conservatively assumed in the model to be the inner edge of the bentonite buffer, into which radionuclides are deposited before diffusing through to the geosphere (described in 5.2.3.3).

Sections 5.2.3.1-5.2.3.5 provide an overview of the processes and assumptions made at each level of the model; the mathematical implementation of these in GoldSim is well established and documented in [238], and a number of important equations referenced throughout can be found in Appendix A of this thesis.

5.2.3.1 Source Term

The source term for the model is based on the UK's spent AGR fuel inventory. AGR fuel pins contain low-enriched (2.90-3.78 %) ceramic uranium oxide pellets sealed within stainless steel cladding (∼300 µm thick) [185]. RWM has periodically updated detailed descriptions of the inventory for disposal [245]. The source term used in the GoldSim model is based on the RWM Derived Inventory (DI) which makes assumptions regarding the nature, scale and timing of future nuclear operations and activities in the UK. The composition of AGR SNF in the DI is based on irradiated fuel from which values of residual specific activity have been deduced,

accounting for radionuclides in stock and those that will arise in the future. For the purpose of this study, it is assumed that the source term is the total inventory of radionuclides present in the AGR SNF at the year 2200, corresponding to an assumed date for the closure of the GDF.

Radionuclides were taken from the ICRP database and specified in the "Species" input module in GoldSim [246]. The International Commission on Radiological Protection (ICRP) is an independent, international organisation, made up of the main commission, Scientific Secratariat, standing Committees and task groups from over 40 countries, whose cause is "Protecting people, animals and the environment around the world from the harmful effects of radiation". Their recommendations form the basis for many policy, regulation, guidance and good radiological protection practices [247]. Individual radionuclide masses was quantified by inserting a Data Element "Initial Inventory" which represents a vector by species, with each radionuclide specified in terms of its total mass. The inventory input (in "Source Inventory Settings"), also accounts for the location of the inventory, relative to engineered barriers and degradation method specified. For the purpose of representing both spent fuel cladding and the wasteform canister, the source was chosen to contain a "double" barrier, implying that in order for radionuclide release to occur, both would have to fail.

5.2.3.2 Waste Package

The waste package is made up of spent nuclear fuel elements, comprising fuel pellets encased in cladding, and the waste disposal container, expected to provide physical containment for 1000s of years [41]. Variability in the corrosion rates and mechanical loads experienced by individual waste canisters leads to uncertainty in the time it will take for a canister to fail and over what duration the remaining canisters will fail. The model was initially built to assume failure will definitely occur across the whole stock of canisters, at a uniform rate determined by a probability distribution function specified in Table 5.2. Stainless steel fuel cladding was expected to fail much sooner than the waste container, over a matter of 100s of years (noting in Chapter 4, an estimate of up to 300,000 years was made based on generalised corrosion only),

due in part to the potential for localised corrosion, but was assumed to be completely intact upon closure (t=0 yr) [41].

Based on the initial inventory and the number of waste packages specified, the model considers each package to contain an identical proportion of the SNF's radionuclides. Once a waste canister and its cladding are breached, wasteform dissolution commences instantaneously. Sorption to the canister, corrosion products or the wasteform have been neglected.

The release rate of radionuclides from SNF pellets encompasses two main processes, instant release and dissolution (Appendix A: Equation 1A). The instant release fraction (IRF) corresponds to the fraction of the inventory expected to be released instantaneously from the surface of the matrix (see Appendix B for details of the IRF% values for radionuclides in spent AGR fuel). The remaining radionuclides were assumed to dissolve at a fractional rate, defined by a rate constant, k (%.yr^{-1}), the matrix dissolution rate [248]. Only a few preliminary studies on AGR matrix dissolution have been conducted, with the focus on its behaviour in oxic conditions. The release fraction of uranium, indicative of the matrix rate of dissolution, was of the order 3.7×10^{-6} -3.7×10^{-5} %.yr^{-1}, similar to those observed for LWR dissolution [176]. International studies of matrix dissolution however, including those conducted in Finland and Germany, indicate a rate in the region of 10^{-8} -10^{-7} %.yr^{-1}, as was also demonstrated in the SR-Can safety assessment conducted by SKB in Sweden. As radionuclides are released, either as part of the IRF or subsequently by dissolution, they are deposited into the inventory cell.

5.2.3.3 Buffer and Near-Field Geosphere

The design concept utilised assumed the canister is surrounded by bentonite which occupies the void space in the deposition tunnel, making up the next engineered barrier "layer". Transport of the radionuclides through the bentonite buffer and the LSSR geological barrier is dominated by diffusion, and sorption and solubility limitation were implemented in these elements of the model.

The environment is represented in the model by a number of discrete, well-mixed compartments ("cell pathways"), in which radionuclide concentrations do not vary spatially, which allows for the modelling of diffusion to take a similar form to the discretised diffusion equation (Appendix A, Eq. 2A) [244]. Each cell represents a proportion of the path length radionuclides would migrate along and contains details of all solids and liquids present in that part of the pathway. Diffusive mass flux links were placed between each compartment of the buffer to represent diffusion "diffusive flux" of mass across the compartment interface (Appendix A, eq. 3A) and accounts for variance in radionuclide concentration in the reference fluid in adjacent compartments and the geometry of the diffusive pathway [238]. Each compartment is subject to incoming and outgoing diffusion of radionuclides, radionuclide decay and ingrowth (Appendix A, Eq. 4A).

It was assumed at the time of GDF closure that radionuclide concentration was proportional to the mass present in the compartment and subject to solubility limitation. The diffusive mass flux dynamics through the buffer is the same as those from the buffer to the geosphere, and between cells in the geosphere (diffusion dominated).

5.2.3.4 Overlying Geosphere

The overlying geosphere in the model was made up of advection dominated chalk, represented by a cell network that spanned the remaining groundwater flow path length. The lower half of the geosphere, closest to the repository, represented a reducing environment and the upper oxidising, reflected in the solubility and sorption characteristics implemented in each. The simplest way to model advection through the overlying chalk was to treat it as migration through a porous medium, expected to take thousands of years [244], and which assumed that all mass transferred from a single cell was equal to the mass entering the adjacent downstream cell (Appendix A, Eq. 6A).

5.2.3.5 Biosphere

Radionuclides discharged from the overlying geosphere into a biosphere "sink" at a mass transfer rate, from which radiological risk was ultimately derived. The mass flux discharge from the overlying geosphere (Appendix A, Eq. 7A) was converted into an activity flux ($Bq.yr^{-1}$); the radionuclide flux could then be converted into an effective dose to members of the public. This was done by utilising dose conversion "biosphere" factors (H_{PEG}), generated by biosphere models [249], [250]. These factors make assumptions about climate conditions, the location of the GDF relative to the community at the surface and the lifestyle habits of those communities, to enable the generation of the effective dose ($Sv.yr^{-1}$) to PEGs (Appendix A, Eq. 9A-10A). Assumptions and behaviours factored into their generation included:

- Ingestion of:
  - crops grown in soil polluted by groundwater contaminated by radionuclides
  - products originating from animals grazing in the discharge area and areas watered utilising contaminated surface groundwater
  - freshwater fish from sources within the area of discharge
  - soil (inadvertently) curing consumption of produce grown in contaminated discharge area
- Inhalation of dust
- External irradiation (originating from contaminated land)

Dose conversion factors have been calculated for multiple groundwater pathways, which account for differing degrees of potential exposure. As part of the 2016 Generic Post Closure Safety Assessment (gPCSA), conversion factors for three main pathways, the groundwater, well and marine pathways were generated; however most base scenarios in the gPCSA do not consider the latter as it exhibits the lowest dose per unit release [240].

In order to calculate a value of radiological risk, a constant of proportionality, "risk factor" (r), of 0.06 Sv^{-1}, was applied to the effective dose [251]. For annual effective doses below 100 mSv, assumed to be the case with the post-closure period and radiological impact of groundwater releases associated with geological disposal, 0.06 Sv^{-1} is considered an apt, detriment-adjusted coefficient of risk [252]. The result, an annual radiological risk, of units yr^{-1}, provided an indication of the chance of death to a PEG, due to the release of radionuclides from the GDF.

5.3 Model Verification

GoldSim is a recognised tool for dynamic mathematical modelling, however, it was important to verify the 1-D model used in this study before utilising the results to make judgements relevant to the regulation of the GDF.

5.3.1 Methodology

Testing the model against experimental data was not an option because of the lack of available information on radionuclide transport in geological settings. RWM undertook a four step process to computational model verification involving: 1) Self-checks; 2) Independent checks; 3) Result sense checks (running the model to determine if it generates results that appear sensible e.g. weakly sorbing radionuclides dominating risk) and 4) comparison of the results with their own simplified analytical models, which aim to provide an insight into the key performance measures of a generic geological disposal system [240].

In much the same way, the approach used to verify the model used in this study included a self-check of the model and data input, an independent review by an experienced GoldSim user specialising in radionuclide release modelling and comparison of results against RWM results, utilising the same input data.

5.3.2 Data for Verification

The aim of this work was to use the simplified 1-D GoldSim model to benchmark against and approximately reproduce the results from a more sophisticated RWM calculation, to justify its use in subsequent sensitivity analysis. RWM made data available from their verified total system model (TSM) for radionuclide release (including individual radionuclide flux profiles) for the disposal of AGR spent fuel in a hypothetical LSSR geological setting. Shared input data between the RWM model and the model developed in this research project is displayed in Table 5.1.

Table 5.1: Input data utilised for the verification of this model [240].

Property	Value/Range	Property	Value/Range
Hydraulic conductivity ($m.s^{-1}$)	LSSR: LogUni(2×10^{-14}, 5×10^{-13}) Chalk (Depth Variable): LogUni(1×10^{-9}, 1×10^{-7}) LogUni(1×10^{-7}, 1×10^{-5}) LogUni(1×10^{-5}, 1×10^{-3})	Inventory masses (g)	See Appendix B.
Hydraulic Gradient	Chalk: 1×10^{-4}	Canister failure time (yr)	LogTri (1.00×10^{4}, 5.00×10^{4}, 9.00×10^{4})
Solubility Limits	See Table 5.4.	Transport porosity	LSSR: 0.18; Chalk: 0.01-0.05
Sorption Coefficients	See Appendix B.	Dry Density ($kg.m^{-3}$)	LSSR: 2.27×10^{3}; Chalk (Depth Variable): 1.97×10^{3}, 1.85×10^{3}, 1.65×10^{3}
Matrix Dissolution Rate (yr^{-1})	LogTri(1×10^{-8}, 1×10^{-7}, 1×10^{-6})	Instant Release Fraction (%)	See Appendix B

There are limitations with this approach, but for the purpose of the sensitivity study, they were considered to be acceptable. Some difficulties arose due to the limitations on the accuracy of

some of the modelling methods employed, particularly related to how flow through the overlying chalk layer is represented. NWS is reviewing its approach in this area, and this therefore represents an element of uncertainty in calculations and models verified against them.

5.3.3 Verification Results

Utilising the inputs and data provided by RWM, for individual radionuclide and total (all radionuclides) annual radiological risk, the GoldSim model was used to predict the annual radiological risk. The comparison with the RWM calculations is shown in Figure 5.2. Figure 5.2a shows the comparison of the GoldSim (AM05) model predictions with those of the RWM model for the well pathway. This pathway considers exposure to radionuclides that have migrated to an aquifer from which well water, used for domestic purposes and small-scale irrigation, has been drawn. The second pathway considered in this study, a "natural discharge" pathway, was concerned with the migration of radionuclides to the biosphere "sink" via the geology's intrinsic groundwater pathways. Each pathway, detailed in [98], contributed to how risk was determined through the use of biosphere dose conversion factors. Figure 5.2b shows the comparison of the models for the Natural Discharge Pathways.

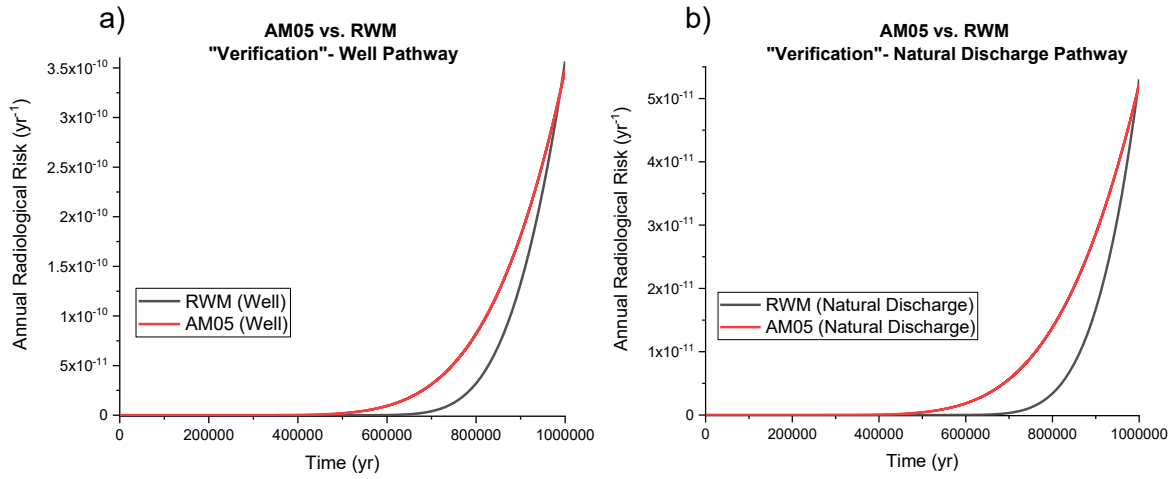


Figure 5.2: a) Annual radiological risk profile comparison for the "Well Pathway" only, b) Annual radiological risk profile comparison for the "Natural Discharge" pathway only.

It could be seen that within the simulation timeframe of 1 million years, that the two models grow exponentially to reach similar levels of peak annual radiological risk ($\sim 3.5 \times 10^{-10}$ yr^{-1} for the well pathway and 5.1×10^{-11} yr^{-1} for natural discharge). However, this GoldSim model predicts higher risks in the period between 500,000 and 1 million years. Given the multiple differences in the models, and the uncertainties associated with the RWM model, the results of the verification exercise gave confidence that GoldSim 1-D model was reasonably able to predict more conservative levels of risk associated with the disposal of AGR fuel.

5.3.4 Model Adequacy for Risk Evaluation

The model developed and discussed throughout this chapter was created and benchmarked against data provided from RWM's total system model, utilised in their safety assessment and risk analysis activities. This model does not stringently replicate the structure of RWM's TSM, and as stated in 5.2.3 utilises a number of simplifications to ensure the approach taking throughout these studies was intentionally conservative.

However the results of this verification exercise showed that to a reasonable degree, this simplified model was able to generate a profile of annual radiological risk with similar values of peak risk in the first 1 million years post-closure. This provided an adequate level of assurance that the 1-D model was appropriate for use in further indicative sensitivity studies or scenarios such as those described throughout the rest of Chapter 5.

5.4 Base Case Assumptions

As previously stated, GoldSim allows the for probabilistic simulation of complex systems in order to account for uncertainties in a number of key input parameters. As such the simulation of the base case (and subsequent sensitivity studies) took a multi-realisation approach. A realisation corresponds to a single model run within a Monte Carlo simulation and represents a possible

path the system could take over time. In each case scenario, 100 realisations of the model were performed. This number of realisations was chosen to ensure a sufficient number of variable combinations were computed to provide a large enough sample size for errors to be drawn from the data and instil a satisfactory level of confidence in the average radiological risk calculated, whilst managing time and computing capability.

The base case aimed to simulate the illustrative disposal concept for AGR SNF in a GDF located in lower strength sedimentary rock at a depth of 500m. The waste canister for AGR SNF in LSSR is currently assumed to take the form of a 120 mm thick carbon steel waste "Variant 2" canister [253]. Under the reducing conditions promoted by bentonite, general corrosion is likely to be the only mechanism of canister degradation and canisters can be projected to survive for as long as 120,000 years.

In the base case, it was assumed that a total of 2,190 AGR canisters were placed in the GDF (based on data from the 2013 DI) [245]. The first canister was assumed to fail according to a pre-determined probability distribution function, at a time between 10,000-90,000 years, with subsequent, uniform failure of the remaining canisters over a 1,000-25,000 year period following the first failure. It was necessary to represent the initial canister failure time this way to account for uncertainties related to a lack of a specific GDF location. The canister was treated within this model as a double barrier entity; once the initial canister was breached, a second "inner" barrier, representing stainless steel AGR fuel cladding, instantaneously began to corrode, at an assumed rate of 0.1 µm.yr^{-1}.

The IRF, corresponding to those radionuclides located at grain boundaries and pellet surfaces, was assumed to be released over a 10 year period following disposal container and SNF cladding failure. The second, slower release associated with the remaining radionuclides that are bound in the fuel pellet matrix, were released into groundwater at a fractional mass rate of 10^{-7}% yr^{-1}. Table 5.2 summarises the key input variables for the base case calculation.

Table 5.2: Input data for the base case calculation.

Parameter	Data Value
Number of waste canisters	2190
Matrix Dissolution Rate (%.yr^{-1})	10^{-7}
Initial Failure Time (yr)	LogTri(1×10^4, 5×10^4, 9×10^4)
Duration of Canister Failure (yr)	Uni(1000, 2.5×10^4)
Canister Failure Mode	Uniform
Solubility Limits	Examples (Table 5.5)
Sorption to Bentonite	Examples (Table 5.6)
Bentonite Thickness (m)	0.725
Sorption to LSSR	Examples (Table 5.7)
Biosphere Factor	Well + Natural Discharge
Depth (m)	500

5.5 Sensitivity Study Assumptions

In order to analyse the impact of the factors that could affect the risks associated with the disposal of SNF, a number of "sensitivity" studies were carried out. The factors studied related the performance of the engineered barriers, the assumed properties of natural barriers, the depth of the GDF and assumptions made about the biosphere pathway. Table 5.3 lists the factors that were studied along with the sensitivity range investigated.

5.5.1 Matrix Dissolution Rate

The dissolution of the fuel pellets and the subsequent release of radionuclides can depend upon a number of factors and the sensitivity this may have on the risk to PEGs from differing rates of dissolution is an important factor in assessing the safety of the disposal of SNF for future generations. The values utilised were derived from waste solubility, flow conditions in

Table 5.3: Key factors influencing the evaluation of risk.

	Factor	Sensitivity Range
1	Matrix Dissolution Rate	1×10^{-5} to 1×10^{-8} % yr^{-1}
2	Canister Failure Time	0 to 100,000 yrs
3	Canister Failure Mode	Simultaneous failure; Uniform failure
4	Solubility Limits	-1 to 7 $mol.m^{-3}$ (radionuclide dependent)
5	Bentonite Thickness	0.363-0.725 m
6	Radionuclide Sorption	0 to 984 $m^3.kg^{-1}$ (radionuclide dependent)
7	Water Flow Rate	10-1000 % (of Base Case flow)
8	Biosphere Factor	Natural discharge pathway only; Well pathway only; both.
9	GDF Depth	200-1000 m

the engineered barriers and the surface area of the wasteform available for dissolution [241]. They represent rate constants, assuming a time-independent, uniform rate of dissolution once groundwater has made contact with the spent nuclear fuel.

5.5.2 Canister Breach Time

The time at which spent fuel disposal canisters is breached is sensitive to a number of factors, including corrosion mechanisms, failures in quality control e.g. canister lid weld defects and mechanical stresses resulting from the expansion of buffer materials. The GDF design will dictate the canister material chosen and thus the chemical and physical characteristics of the canister. The geological setting or design for the UK's GDF has yet to be decided, but in the interim it is vital to understand how the time the canister fails relates to the risk posed to the PEGs.

5.5.3 Canister Breach Mode

Which mechanism(s) dominate the failure of the canisters will be linked to the GDF design. Modes of failure considered here included simultaneous failure, whereby all canisters were breached concurrently or uniform failure in which canisters failed periodically over a set amount of time. It is important to understand the relationship between risk to the PEGs and the way canisters fail over time, as it might impact upon the way in which existing and future waste packages are produced, stored, transported or disposed of.

5.5.4 Solubility of Radionuclides

Increased solubility in pore and groundwaters could increase the proportion of harmful, long-lived radionuclides that are able to migrate to the biosphere over a set period of time, thus increasing the dose to PEGs. Within the model, solubility limits describing the maximum concentration each radionuclide may ably reach in bentonite-conditioned porewater were represented by log triangular distribution functions for transport in the bentonite buffer layer adjacent to the waste package (with the exception of uranium which was represented by a cumulative probability distribution function derived from [254]). These limits were derived from data on reference groundwaters and the Nagra/PSI thermodynamic database. The distribution function for each radionuclide is specific to each radionuclide and are specified in Table 5.4.

Table 5.4: Solubility limits input into GoldSim model.

Element	Solubility Limit/ mol.m^{-3}	Element	Solubility Limit/ mol.m^{-3}
Ac	LogTri (5×10^{-5}, 0.001, 0.03)	Pb	LogTri(2×10^{-5}, 0.002, 0.08)
Ag	LogTri (1×10^{-7}, 0.003, 0.003)	Pd	LogTri(1×10^{-7}, 5×10^{-5}, 2×10^{-4})
Am	LogTri (5×10^{-5}, 0.001, 0.03)	Pu	LogTri(3×10^{-6}, 5×10^{-5}, 0.001)
C	LogTri(0.6, 3, 7)	Ra	LogTri(4×10^{-9}, 2×10^{-8}, 5×10^{-5})
Cl	-1	Se	LogTri(2×10^{-8}, 5×10^{-6}, 0.01)
Cm	LogTri (5×10^{-5}, 0.001, 0.03)	Sm	LogTri(3×10^{-4}, 5×10^{-4}, 9×10^{-4})
Cs	-1	Sn	LogTri(5×10^{-6}, 1×10^{-5}, 1×10^{-4})
I	-1	Sr	LogTri(0.003, 0.02, 0.1)
Mb	LogTri(0.001, 0.001, 0.01)	Tc	LogTri(1×10^{-6}, 4×10-6, 1×10^{-5})
Nb	LogTri(1×10^{-5}, 0.03, 0.1)	Th	LogTri(2×10^{-4}, 7×10^{-4}, 0.003)
Ni	LogTri(0.01, 0.03, 0.08)	U	CDF
Np	LogTri(3×10^{-6}, 5×10^{-6}, 1×10-5)	Zr	LogTri(3×10^{-8}, 2×10^{-6}, 2×10-6)
Pa	LogTri(1×10^{-5}, 1×10^{-5}, 0.01)		

Those elements input with a solubility limit of -1 mol.m^{-3} were done so to ensure they were represented within GoldSim as having unlimited solubility.

5.5.5 Bentonite Thickness

Bentonite plays an important role in both the protection of the SNF canister and inhibiting the release of radionuclides from failed canisters. The values displayed in Table 5.3 were derived from the difference in the assumed diameters of the deposition hole and disposal canister; the emplacement tunnel's radius for the design based on the Opalinus Clay concept is 1.25 m and the outer radius of the canister 0.525 m [44]. The larger bentonite thickness values assumes the entire void space between the outer edge of the canister and the inner surface of the tunnel is occupied by swollen bentonite; the lower pessimistically assumed emplacement issues such that

only half of the void was occupied. Understanding the relationship between the thickness of the bentonite engineered barrier and risk to the PEGs is important to the safe design of a GDF.

5.5.6 Radionuclide Sorption

Sorption of radionuclides to bentonite, the LSSR and overlying chalk has the potential to inhibit the transport of radionuclides to the biosphere and alter the risk posed to PEGs, as such it is necessary to understand to what extent sorption to each of these affects the time and scale of radionuclide flux reaching the biosphere. Radionuclide partitioning was achieved through the utilisation of radionuclide sorption coefficients and anion exclusion factors, which accounted for sorption to the surface, and the availability of pores for the exchange of ions between solution and the surface [255]. The sorption coefficients in the bentonite buffer were taken from SKB's SR-Can documents, sourced from their experimental measurements on MX-80 bentonite [218]; sorption coefficients for the geology are derived from the scaling of measurements of sorption in Opalinus Clay [256]. Expert elicitation allowed for the generation of log-triangular distributions of sorption coefficients in the overlying chalk layer [257], [258]. Table 5.5 (Section 5.6.2.5) displays the coefficients for a number of key radionuclides that were utilised in this model. The relationship between the sorption characteristics (and associated uncertainties) and radioactive flux, ergo radiological risk, is important to understanding the safety implications of a GDF's design, material, and geology choices.

5.5.7 Flow Rate

The exact nature of fracture frequency, connectivity and direction in the overlying chalk is unknown due to lack of a definite GDF location. An understanding of the relationship between water flowrate and risk to the PEGs will be important for the siting of a GDF and particularly in geologies where advection acts as the dominant mechanism for groundwater transport, such as the high strength rocks being considered in the UK. It was deemed appropriate, given this

uncertainty, that a range of 1 %-1000 % of the flow rate utilised in the base case was investigated.

5.5.8 Biosphere Factors

As the location of the GDF is yet to be determined, it is impossible to know if the only route through which radionuclides may migrate to the biosphere is via natural discharge through the geosphere, or if there could be migration to features like a well in the overlying aquifer. The impact of either pathway, or a combination of the two, represented in the model by biosphere dose conversion factors, on the annual radiological risk may influence NWS' decision on the location for the GDF.

5.5.9 GDF Depth

The relationship between the depth of a GDF and risk will affect the design considerations for a GDF in terms of worker safety, engineering requirements and the economics of the excavation and associated materials. Appropriate GDF depths are considered to encompass all in the region of 200-1000 m below surface, thus it is important to understand whether varying the depth of a repository will significantly increase the annual risk associated with disposal, and to gauge what compromises or concessions may be permissible in also meeting requirements related to the economic, engineering and worker safety aspects of the programme.

5.6 Results and Discussion

5.6.1 Base Case

The risk to PEGs was calculated from the activity flux associated with the release of radionuclides into the biosphere (discussed in Section 5.2.3.5).

The inventory activity utilised in calculations reflected the total inherent activity of radionuclides in 2200, the point at which the post-closure phase commences. Notably, the activity flux was dominated by long lived radionuclides, in particular chlorine-36, iodine-129 and selenium-79, all of which equilibrate or peak at values above 10^3 Bq.yr^{-1}; Figures 5.4-5.6 display the flux profiles for each of these radionuclides, whilst Figure 5.7 included the total activity flux for all radionuclides.

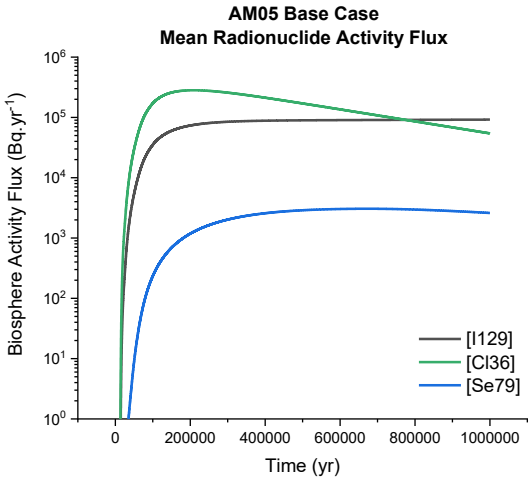


Figure 5.3: Base Case Mean Biosphere Flux Over Time for the Three Dominant Radionuclides

The flux profiles in Figures 5.4-5.6 display the mean activity flux for each of iodine-129, chlorine-36 and selenium-79 respectively, along with the distribution of observed results at different percentiles ranging from the observed maximum and minimum (most extreme values) to 25th/75th percentile and the 5th/95th percentile which were be used as the measure of error in risk profiles generated throughout the subsequent sensitivity studies.

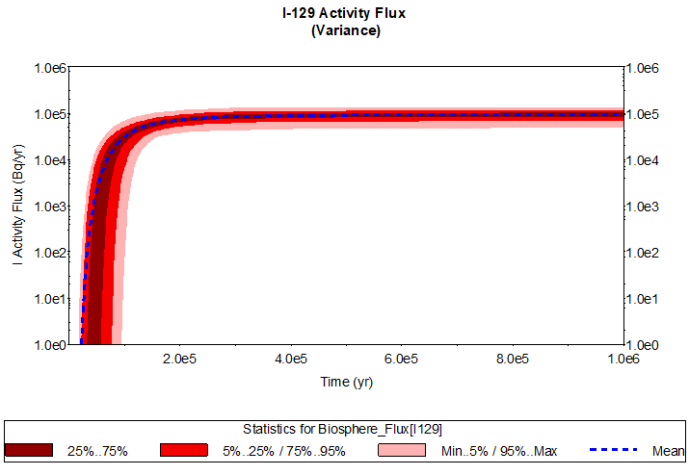


Figure 5.4: Base Case Mean Biosphere Flux Over Time for iodine-129.

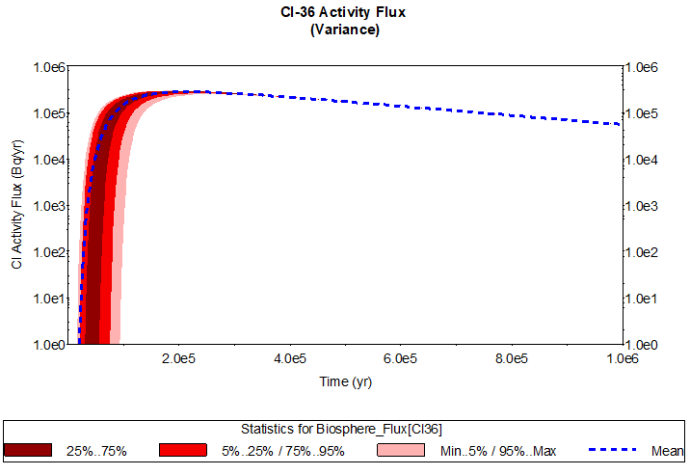


Figure 5.5: Base Case Mean Biosphere Flux Over Time for chlorine-36.

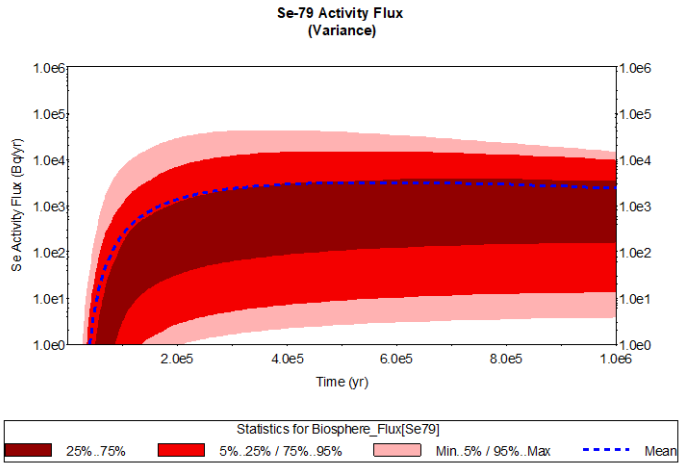


Figure 5.6: Base Case Mean Biosphere Flux Over Time for selenium-79.

The flux of selenium-79 displayed the most variance, and indicated that the earlier emergence of flux at the biosphere resulted in a larger activity flux overall (and vice versa). The profiles for chlorine-36 and iodine-129 were much more uniform across all realisations, and their contribution to the annual radiological risk, consistent.

The corresponding value of annual radiological risk for each of these radionuclides is displayed in Figure 5.7, along with the cumulative risk for all radionuclides in the inventory. Of note was the dominance of iodine-129 in its contribution to overall risk, likely due to its inherently long half-life, significant quantity in the inventory and aspects of the dose to risk conversion "biosphere factor" for iodine-129.

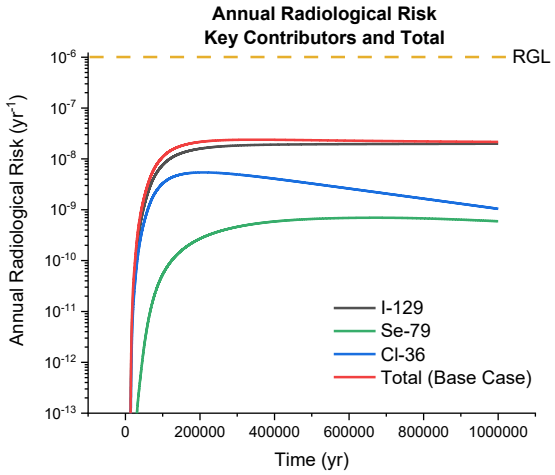


Figure 5.7: Base Case Mean Annual Radiological Risk Over Time for Key Radionuclides.

For the Base Case it was observed that the annual risk began to stabilise in the biosphere after 100,000 years, peaking at approximately 2.36×10^{-8} yr^{-1} around ~300,000 years. This corresponds to approximately 1 death in 42 million potentially exposed persons per year for the base case at peak risk. This was almost 2 orders of magnitude below the risk guidance level (RGL) set out in both the Environment Agency's Guidance for Requirements on Authorisation (GRA) and the advice of the Health and Safety Executive [259], [260]. The HSE states an individual annual risk of death corresponding to a 1 in 1 million, or 10^{-6} yr^{-1}, serves as an appropriate guideline for the boundary between acceptable and tolerable risk, which can be regarded as insignificant and adequately controlled in keeping with a dutyholder's responsibility to reduce risks so far as is reasonably practicable (SFAIRP).

5.6.2 Sensitivity Studies

As discussed in Section 5.5, a number of sensitivity studies were carried out to investigate the impact of key parameter variations on the radiological risk generated from the base case scenario. In these studies, the Base Case model was used and only the parameter being investigated in the sensitivity study was altered (see Table 5.3). The calculations conducted in line with

sensitivity factors outlined in Sections 5.5.1-5.5.9 assumed the radionuclide release and transport characteristics of the base case simulations, other than the selected sensitivity factor.

5.6.2.1 Matrix Dissolution Rate

The dissolution rate of oxide spent fuels may be adversely affected by a number of environmental and emplacement related conditions. The use of appropriate "averaged" values allows for a simple representation of the expected dissolution behaviour of spent fuel, which will in reality, decrease over time.

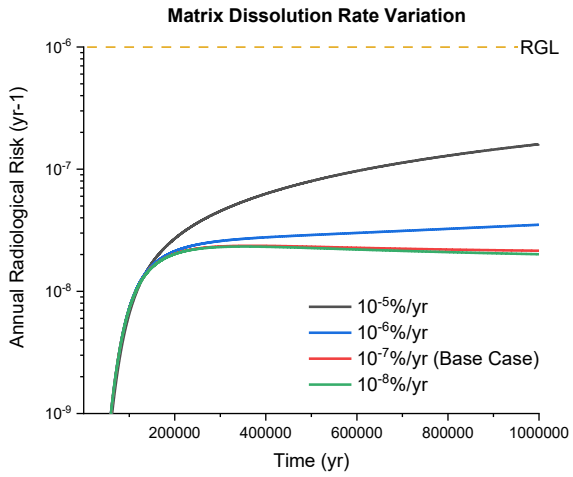


Figure 5.8: Mean Annual Radiological Risk for the Matrix Dissolution Rate Sensitivity Study.

The peak risks associated with the highest dissolution rates (10^{-6}%; 10^{-5}%) are not shown on this graph as they occurred at approximately 14 million years (1.46×10^{-7} yr^{-1}) and 11 million years (7.67×10^{-7} yr^{-1}) respectively. Nonetheless there was a clear positive correlation between the peak annual risk and the rate of matrix dissolution. Within 1 million years, an order of magnitude separated the peak risks observed for the dissolution rates of 10^{-8} and 10^{-5}%. yr^{-1}; the peak at 10^{-5}% yr^{-1} approximately 1.60×10^{-7} yr^{-1} compared to the 2.32×10^{-8}yr^{-1} observed at the lowest dissolution rate, which also occurred significantly earlier at ~330,000 years. The simulation of dissolution at rate of 10^{-5}% yr^{-1} represents an overly cautious example, and lies

outwith the rate constant values utilised by RWM as part of its own TSM studies [241].

5.6.2.2 Canister Breach Time

The base case assumed that the first canister was breached between 10,000 and 90,000 years and a linear failure rate for the remaining canisters over the following 1,000 to 25,000 years, as shown in Section 5.4. To assess the sensitivity of failure time on the annual risk to the PEG, risk calculations were performed maintaining all of the base case parameters, only varying the canister breach time. The time of first canister breach was manually input across a range of first breach times from 0 to 100,000 years; the annual radiological risk and how it altered with an increase in the time of initial canister failure is displayed in Figure 5.9.

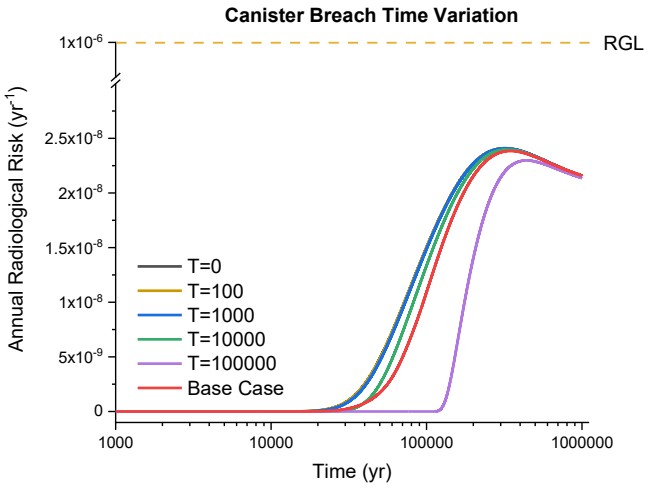


Figure 5.9: Mean Annual Radiological Risk for the First Canister Failure Time Sensitivity Study.

The time taken for risk to emerge was similar for those where failure occurred in the first 1000 years, likely due to the minimum time over which all canisters can fail uniformly, according to the probability distribution function, being 1000 years. The peak annual risk in each case was observed to be $\sim 2.41 \times 10^{-8}$ yr^{-1}. The peak risk values associated with canister breach at t=10,000 years began to deviate marginally; peak risk decreased to $\sim 2.39 \times 10^{-8}$ yr^{-1} and

occurred at ∼317,000 years. The peak risk observed when the first canister fails at 100,000 years is therefore not significantly lower than those exhibited at initial failures between 0-10,000 years. The peak risk for the longest initial breach time (t=100,000 years) occurred at approximately 420,000 years at a value of 2.29×10^{-8} yr^{-1}, a reduction of only 710^{-10} yr^{-1} compared to the peak risk observed in the base case, and only 1.2×10^{-9} yr^{-1} lower than the shortest breach time (t=0 years), as in Figure 5.9. The decrease that is observed in each peak can be attributed largely to the decay of chlorine-36 ($t_{1/2}$= 301,000 years), with the effect of shorter-lived radionuclides decaying prior to canister failure for the t=100,000 year case. This analysis indicated peak annual risk to PEGs to be relatively insensitive to the time at which the first disposal container was breached, instead emphasising the likely importance of the engineered and geological barriers in perturbing radionuclide migration out of the GDF.

5.6.2.3 Canister Breach Mode

The base case scenario assumed uniform failure of all remaining containers once the first disposal container had failed. The simultaneous failure of all containers, and its impact on radiological risk according to the 1-D model, is shown in Figure 5.10.

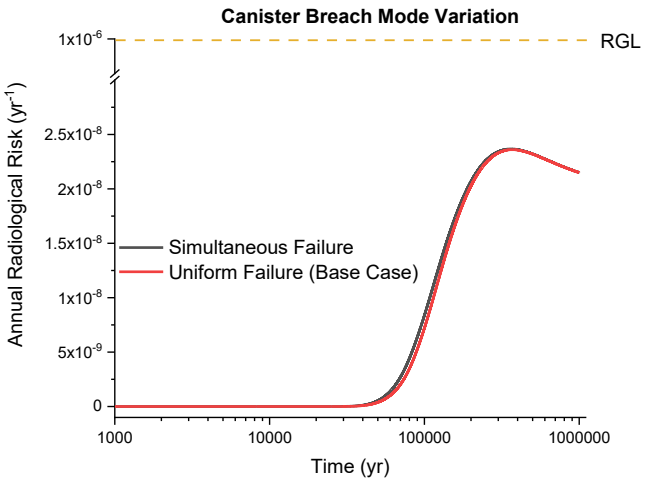


Figure 5.10: Mean Annual Radiological Risk for the Canister Failure Mode Sensitivity Study.

It was noted that the simultaneous failure of all canisters did not appear to increase the peak annual radiological risk to people in the PEGs, still occurring at ~300,000 years at a risk of 2.36×10^{-8} yr^{-1}. Although the risk profile developed slightly earlier than in the base(uniform failure) case, the timeframe over which uniform failure was assumed to occur was sufficiently short that an almost identical risk profile was generated for simultaneous container failure. The results of this sensitivity study indicated that the peak annual risk to the PEGs in the biosphere was not sensitive to a change in the mode of SNF canister failure, though does not give any indication of whether either scenario, or an alternative, is most likely to occur or result in significantly high radiological risks.

5.6.2.4 Solubility Limits

Radionuclide solubility limits for bentonite conditioned groundwater were simulated using probability distribution functions, such as log triangular and cumulative distribution functions (CDFs) to reflect uncertainties. To analyse this sensitivity, the upper bound values from these functions were input to incur the highest plausible values of solubility and assess the potential impact of increased solubility on the annual radiological risk. Examples for some important radionuclides are included in Table 5.5.

Table 5.5: Solubility limit upper bounds for selected radionuclides.

Radionuclide	Solubility Limit Upper Bound/ $mol.m^{-3}$	Solubility Limit Lower Bound/ $mol.m^{-3}$
I-129	Unlimited	Unlimited
Cl-36	Unlimited	Unlimited
Se-79	0.01	2×10^{-8}
Pu-238 to Pu-241	0.001	3×10^{-6}
Th-228 to Th-232	0.003	2×10^{-4}
U-232 to U-238	0.1 (from CDF)	3.2×10^{-9}

It was observed, as in Figure 5.11, that increasing the radionuclide solubility in bentonite groundwaters increased the peak annual radiological risk to a value of approximately 2.60×10^{-8} yr^{-1} and appeared to be delay the peak risk from occurring until ~400,000 years. It was evident from the profile shape, including when significant risk began to emerge, that peak annual radiological risk was not substantially altered by an increase in the proportion of groundwater soluble radionuclides, likely due to the dominant radionuclides (i.e. iodine-129, chlorine-36) possessing ~unlimited solubility under the assumed conditions.

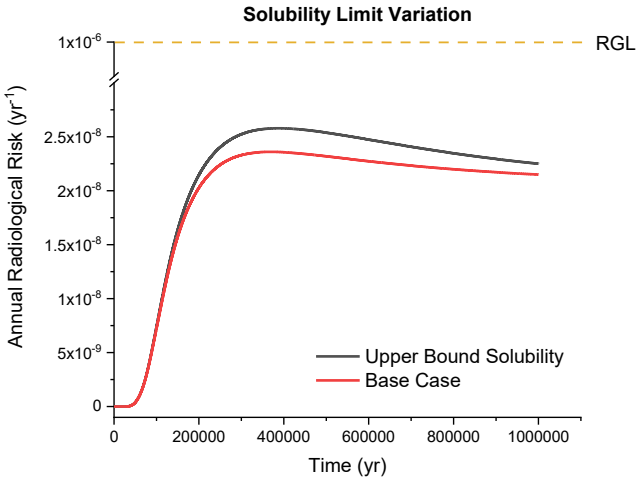


Figure 5.11: Mean Annual Radiological Risk for the Solubility Limit Sensitivity Studies.

5.6.2.5 Bentonite Physical Parameters

The thickness of bentonite emplaced between the canister and the excavated disposal tunnel was varied to highlight how the affect of its diffusive and sorptive capabilities impacted on the annual radiological risk to PEGs. This was achieved by reducing bentonite thickness by 50 %.

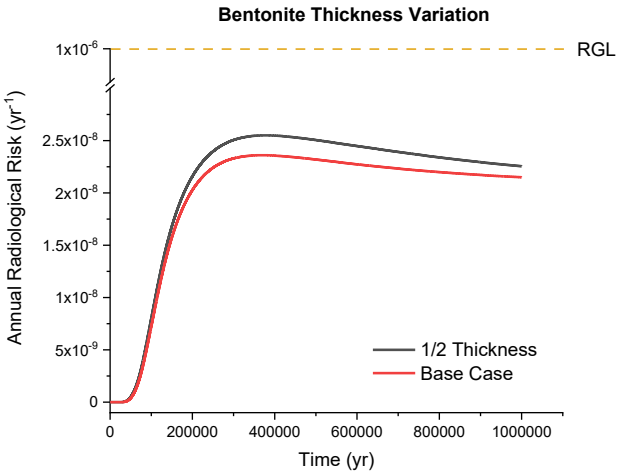


Figure 5.12: Mean Annual Radiological Risk for the Bentonite Thickness Sensitivity Studies.

Figure 5.12 highlights the result of a reduction in bentonite thickness. The overriding conclusion was that it led to an increase in the peak annual radiological risk. The risk increased from the base case value of 2.36×10^{-8} yr^{-1}, to 2.55×10^{-8} yr^{-1}, an increase of ~8%, which was not considered significant at these risk levels, but may be when considering a larger source term. In that instance it might be that additional onus is placed on other EBS to provide increased levels of containment to minimise the associated increase in risk. The time to reach the peak value of radiological risk observed marginally increased with a decrease in bentonite thickness, occurring at ~360,000 years. This reduction in bentonite thickness also meant that the time taken to reach a risk value equal to the peak risk for the base case was ~240,000 years, much earlier than as was observed for the base case scenario.

5.6.2.6 Radionuclide Sorption

Bentonite Sorption

The effect of reducing the sorption of radionuclides to the bentonite buffer is displayed in Figure 5.13. The sorption coefficients utilised for a number of important radionuclides are displayed in

Table 5.6; those values in bold represent the lower bound or "least sorptive" case. It was seen that reducing sorptive capacity increased the annual radiological risk, as would be expected. It was important to note that the decrease in sorption only led to a small increase in peak radiological risk of approximately 6×10^{-10} yr^{-1}, resulting in a peak annual radiological risk of 2.42×10^{-8} yr^{-1}, remaining far below the RGL.

Table 5.6: Sorption coefficients in the bentonite barrier for selected radionuclides.

Radionuclide	Sorption Coefficient $m^3.kg^{-1}$
I-129	**0**
Cl-36	**0**
Se-79	LogTri (**0.003**, 0.04, 0.4)
Pu-238 to Pu-241	LogTri (**0.2**, 2, 20)
Th-228 to Th-232	LogTri (**6**, 63, 700)
U-232 to U-238	LogTri (**0.0095**, 0.095, 0.95)

It was noted that the increase in risk was likely due to the layer being so thin relative to the total path length of the groundwater pathway to the biosphere, and the fact that those radionuclides shown to dominate the release to the biosphere do not sorb to the bentonite, and as such are unaffected by a reduction in capability.

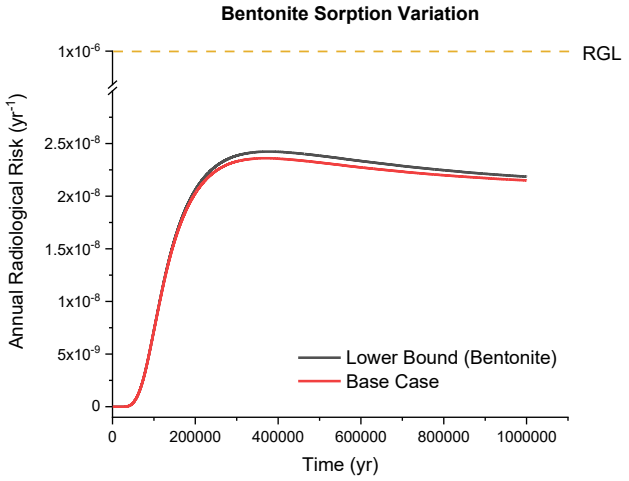


Figure 5.13: Mean Annual Radiological Risk for the Bentonite Sorption Sensitivity Studies.

LSSR Sorption

One of the favourable characteristics of the lower strength sedimentary geology is its ability to sorb elements, including important radionuclides, and hence reduce radionuclide migration to the biosphere. The ability for the geology to sorb was represented in the model by sorption/anion exclusion coefficients that took the form of probability distribution functions. Figure 5.14 shows the effect of reducing the sorption capability of the geology, to the lower bound from the distribution function, versus the mean (base case). The sorption coefficients employed for a number of important radionuclides are presented in Table 5.7. Those in bold represent the lower bounds employed in this sensitivity and later, in the "worst parameter" scenario simulations.

Table 5.7: Sorption coefficients in the LSSR geological barrier for selected radionuclides.

Radionuclide	Sorption Coefficient $m^3.kg^{-1}$
I-129	**0**
Cl-36	**0**
Se-79	**0**
Pu-238 to Pu-241	LogTri (**1**, 20, 300)
Th-228 to Th-232	LogTri (**10**, 50, 200)
U-232 to U-238	LogTri (**0.5**, 20, 200)

It was seen that utilising the lowest sorption values from Opalinus Clay data in the LSSR layer resulted in very little deviation in the risk profile generated versus the base case. The peak risk of 2.45×10^{-8} yr^{-1} was only marginally larger than that observed in the base case, inferring that even if processes involving organic complexants or a reduction in pH due to interactions with co-located, cementitious backfills were to occur and contribute to a decrease in the ability of the geology to sorb, sufficiently low risk levels could be maintained.

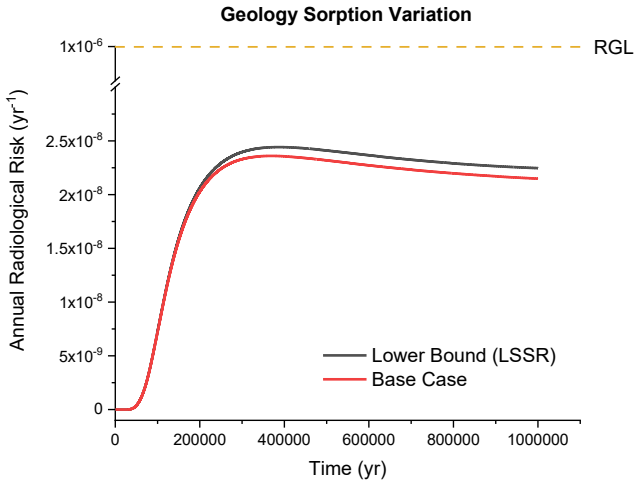


Figure 5.14: Mean Annual Radiological Risk for the LSSR Sorption Sensitivity Studies.

Figure 5.15 shows the impact of removing all sorptive capacity in the geological (LSSR) barrier

for comparison.

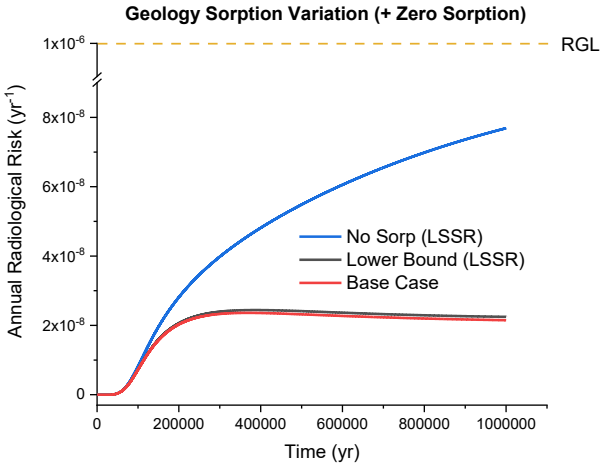


Figure 5.15: Mean Annual Radiological Risk for the LSSR Sorption Sensitivity Studies.

In the extreme case where the sorption capacity of the LSSR was reduced to zero, the annual radiological risk continued to rise until ∼2 million years, and peaked at around 7.7×10^{-8} yr^{-1}. This represented a significant increase on both the base case and lower bound sorption study but still below the current RGL. It should be noted that the likelihood of complete loss of sorption in LSSR is extremely low. As was the case with the bentonite sensitivities, the material properties of the LSSR were varied, though inconsequential deviance from the base scenario was observed.

Overlying Chalk Sorption

Advection dominates groundwater flow through the overlying chalk lithologies, being highly fractured and exhibiting low transport porosity (connected pore networks for groundwater flow). As such the sorption of radionuclides was not expected to occur to a significant degree. This assumption was confirmed by the results obtain for this sensitivity, displayed in Figure 5.16. Table 5.8 contains the sorption coefficients utilised in the overlying chalk layers for a selection of radionuclides.

Table 5.8: Sorption coefficients in the overlying chalk barrier for selected radionuclides.

Radionuclide	Sorption Coefficient $m^3.kg^{-1}$
I-129	**0**
Cl-36	**0**
Se-79	**0**
Pu-238 to Pu-241	LogTri (**0.0055**, 0.055, 0.55)
Th-228 to Th-232	LogTri (**0.0045**, 0.045, 0.45)
U-232 to U-238	LogTri (**0.0095**, 0.095, 0.95)

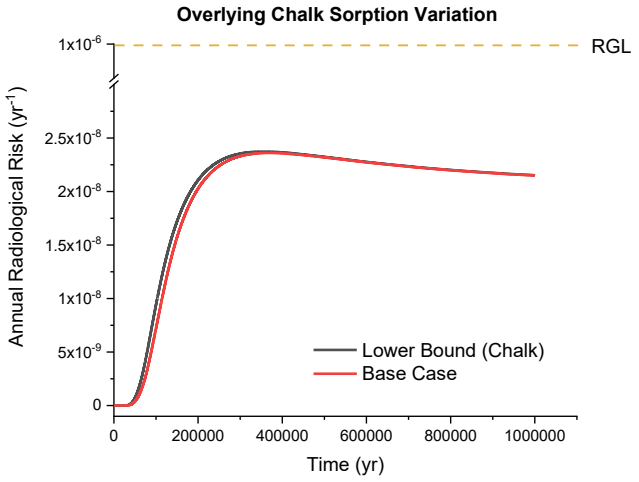


Figure 5.16: Mean Annual Radiological Risk for the Chalk Sorption Sensitivity Studies.

5.6.2.7 Groundwater Flow Rate

To investigate the impact of groundwater flowrate on the peak risk observed in the biosphere, it was simulated at values between 0.01 and 10 times the groundwater flowrate input in the base case. The results are presented in Figure 5.17.

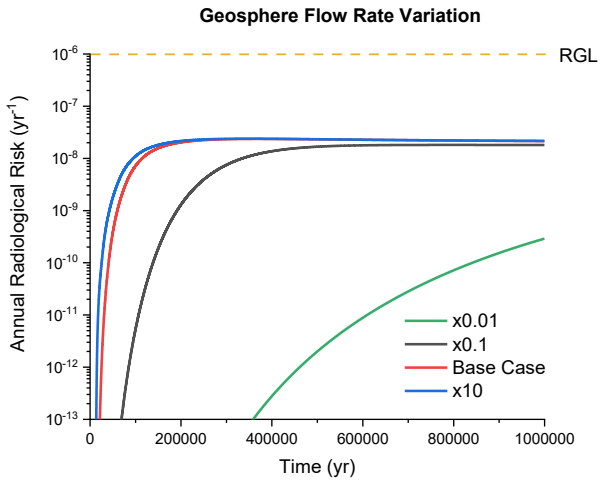


Figure 5.17: Mean Annual Radiological Risk for the geosphere flowrate Sensitivity Studies.

As expected, a decrease in the flow rate led to a decrease in the peak risk observed and increased the length of time required for this peak to occur. Conversely, an increase in flow rate displayed very little impact on the peak annual radiological risk when compared to the Base Case, likely limited by the matrix dissolution rate of the SNF. Evidently a low flowrate (0.1 of the base case) increased the time to reach the peak radiological risk by approximately 300,000 years. For a very low flowrate (0.01 of the base case), the model indicated that the annual radiological risk would peak at 1.87×10^{-8} yr^{-1}, ~14 million years after the closure of the GDF. This flow rate instigated such a delay in some radionuclides reaching the biosphere that the effects of radioactive decay on the peak risk are observable, meaning the peak annual radiological risk remained below the peak observed the base case.

5.6.2.8 Groundwater Pathway (Biosphere Factors)

The biosphere factors, described in section 5.5.8, were input to represent the different potential groundwater pathways associated with the disposal of radioactive waste. The pathways for radionuclide migration will depend ultimately on the location of the UK's GDF. In the calculation of risk, the model considered factors that accommodate natural discharge of groundwater, flow

through to a well or a combination of both pathways. For the purpose of this study the base case assumed both pathways to be viable mechanisms for radionuclide migration to potentially exposed groups in the biosphere and the sensitivity of the impact of a "well" pathway and a "natural discharge" pathway in isolation was studied.

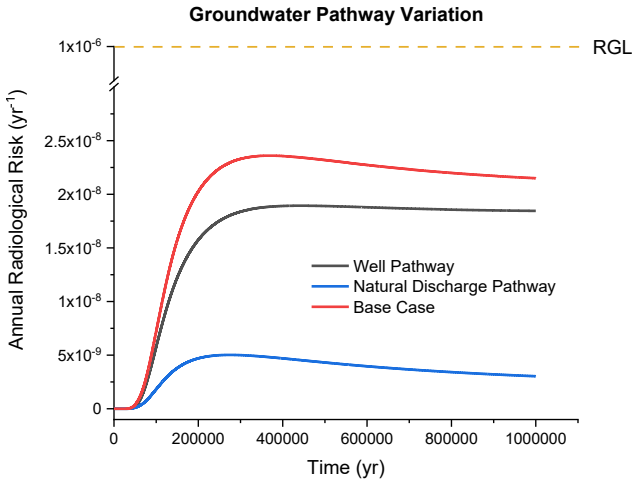


Figure 5.18: Mean Annual Radiological Risk for the Discharge Pathway Sensitivity Studies.

Figure 5.18 displays the annual radiological risk profiles generated for each set of biosphere factors alongside the base case profile. It was evident that the well pathway dominated the combined risk profile, as it resulted in a significantly larger peak radiological risk of $\sim 1.89 \times 10^{-8}$ yr^{-1} compared to that produced by the natural discharge pathway alone (5.01×10^{-9} yr^{-1}). The main inference from this sensitivity was that where possible, a potential GDF location containing a source of water for agriculture or civilian use would likely increase the radiological risk to PEGs, though this remained well below the RGL irrespective of this in this instance.

5.6.2.9 GDF Depth

The depth for geological disposal will depend in part on the location selected for the GDF and its composition at anticipated disposal depths, between 200-1000 m. To investigate the effect of GDF depth of the annual radiological risk sensitivity studies were carried out at depths of 200,

500 and 1000 meters. The results are shown in Figures 5.19 and 5.20.

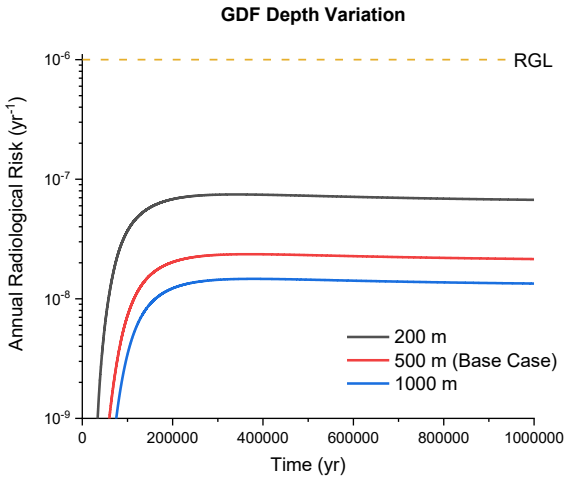


Figure 5.19: Mean Annual Radiological Risk for the GDF Depth Sensitivity Study with constant LSSR thickness.

In these studies, the overlying layers were scaled proportionately from those assumed in the generic design, at a depth 500 m, to provide representative path lengths for each alternate depth. As observed in Figure 5.19, with increased depth came a decrease in the peak risk observed and a delay in its emergence. Radiological release at a depth of 1000 m resulted in an annual radiological risk of $\sim 1.4 \times 10^{-8}$ yr^{-1}, whilst at its shallowest, disposal at 200 m appeared to treble the peak raidological risk observed for the base case (500 m) risk, exhibiting a peak of $\sim 7.49 \times 10^{-8}$ yr^{-1}. The peak observed for the 95th percentile of the 200 m variant increased this further to 9.2×10^{-8} yr^{-1}, effectively a single order of magnitude below the recommended RGL.

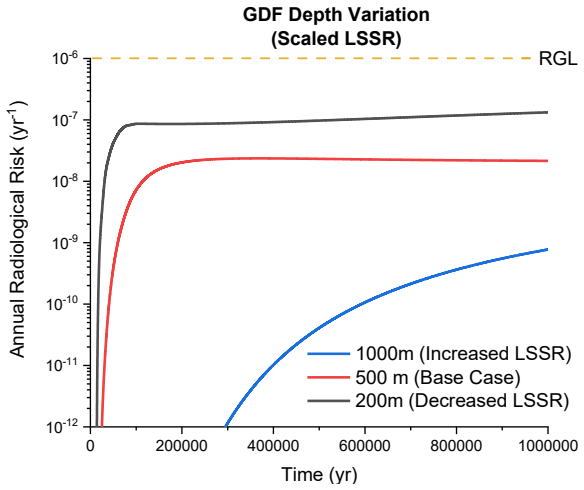


Figure 5.20: Mean Annual Radiological Risk for the GDF Depth Sensitivity Study with scaled LSSR thickness.

Crucially however the variation of depth was not seen to increase the risk beyond unacceptable levels, though this does rely on the assumptions made regarding the thickness of the host geology. Should the thickness of the LSSR decrease, the effects of slowing by diffusion and radionuclide sorption to the LSSR layer would be reduced, increasing the risk. Figure 5.20 displays the of a scaled increase in LSSR thickness with depth. It was noted that a GDF in an LSSR lithology at a depth of 1000m, with significantly thicker LSSR exhibited a maximum radiological risk within the first 1 million years that did not exceed $\sim 1 \times 10^{-9}$, 3 orders of magnitude below RGL. This peaked at 7.75×10^{-10} yr^{-1}, whilst at decreased depth (and thinner LSSR layer) the peak observed at 1 million years was 1.32×10^{-7} yr^{-1}, increasing to 2.07×10^{-7} yr^{-1} $\sim$3 million years post-closure.

5.6.3 Combination of "Worst" Parameters

Utilising the relevant lower or upper bounds for parameters represented by probability distribution functions in the model, and by selecting single values for those parameters that were identified as increasing the peak risk in the sensitivity analysis, a combined “worst parameter” scenario

was investigated. It is important to stress the difference between “worst parameter” and a "worst-case" scenario. In this “worst parameter” scenario, the sensitivities which negatively impacted on the radiological risk to members of the public were combined to provide insight into the overall impact on the risk profile generated. This however would not necessarily represent the “worst-case” scenario, as many complex factors, not considered in this model, will dictate which conditions will contribute to the highest foreseeable level of risk. Figure 5.21 details the results of the worst parameter sensitivity for radiological risk, compared to the base case scenario.

Table 5.9: Comparison of parameters used in base case v “worst parameter” scenario.

	Base Case	“Worst Parameter”
Matrix Dissolution Rate (% yr^{-1})	10^{-7}	10^{-6}
Initial Breach Time (yr)	LogTri(10^4, 50^4, 90^4)	10^4
Breach Mode	Uniform	Instantaneous
Solubility Limits	Table 5.4	Upper Bounds (Table 5.5)
Sorption to Bentonite	Examples (Table 5.6)	Lower Bounds (Table 5.6)
Bentonite Thickness (m)	0.725	0.375
Sorption to LSSR	Table 5.7	Lower Bounds (Table 5.7)
Biosphere Factors	Well+Natural Discharge	Well+Natural Discharge
Depth (m)	500	200

After 1 million years the annual radiological risk reached a maximum at 1.24×10^{-7} yr^{-1} and continued to rise over the next 17 million years; the annual radiological risk peaked at 1.46×10^{-7} yr^{-1} some 18 million years post-closure.

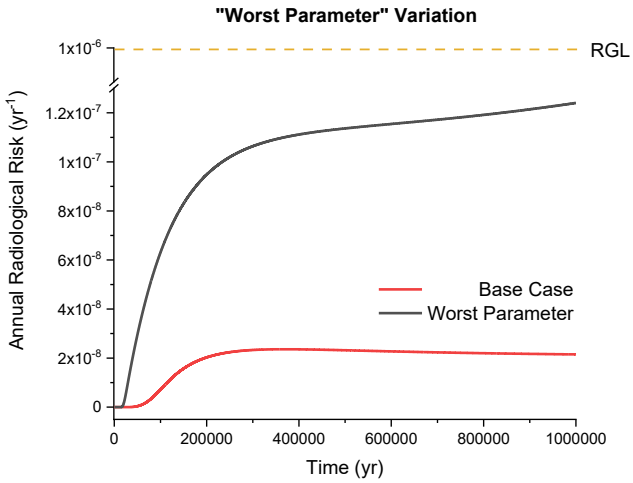


Figure 5.21: Mean Annual Radiological Risk for the "Worst Parameter" scenario.

This significant increase versus the base case was likely governed by the decrease in depth; depth aside, the risk was dominated by solubility and matrix dissolution early on; after 400,000 years the major contribution to the risk profile would appear to come from an increase in the matrix dissolution rate, as it exhibited the largest increase in peak observed risk of any single sensitivity. Overall, there is a substantial increase in annual radiological risk when compared with the base case annual radiological risk, in terms of profile and peak. However at all times the peak risk still remained below the current RGL, even when factoring in potential errors in probabilistic parameters (i.e. utilising data from the 5th/95th percentile).

5.6.4 Comparison of Lower Strength Sedimentary Rock and High Strength Rock Geological Settings

The GoldSim model was modified for application to the disposal of AGR SNF in GDF located in a higher strength rock geological setting, in order to generate data to compare the base case in two different hypothetical geologies. The generic design for AGR disposal in HSR identified as potentially suitable by RWM is based on the Swedish KBS-3V concept, due to the availability

of information relevant to the context of UK disposal [261]. The flow properties were modelled as in the base scenario for the LSSR, diffusion in the bentonite buffer and advection through the HSR and overlying sandstone.

5.6.4.1 Verification of GoldSim Model for HSR

Data from a variant scenario which implemented the early breach of a single SNF canister (by RWM) was used to verify the GoldSim (herein "AM05") model. The AM05 model predictions were based on a single realisation of this variant, for the well pathway only. The same procedure for model verification was followed as described in Section 5.3. Figure 5.22 provides a comparison between results provided by RWM for the annual radiological risk and those of the AM05 model.

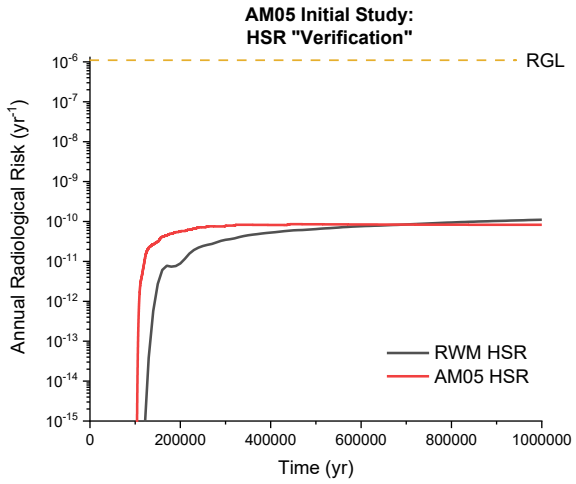


Figure 5.22: Mean Annual Radiological Risk for the for the Verification of the AM05 HSR Model.

The results shown in Figure 5.22 provide confidence in the application of the AM05 HSR model, which was used to generate data for the disposal of AGR SNF in a new base case in a HSR geological setting. The results were compared with those of the AGR SNF (LSSR) base case (well flow rate only) model. Figure 5.23 displays the results of these simulations.

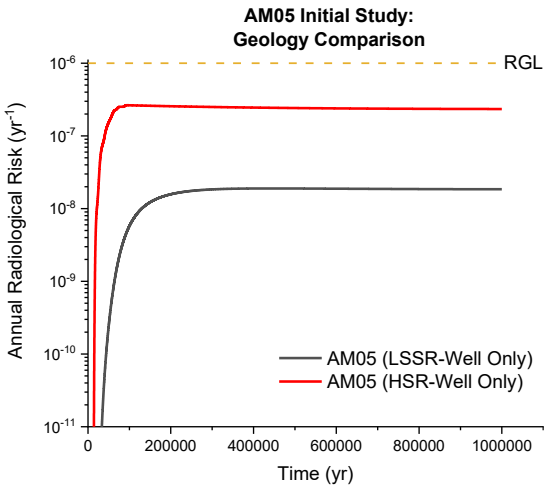


Figure 5.23: Comparison of the Annual Radiological Risk for a GDF in LSSR and HSR.

Results indicated that the peak annual radiological risk in the first 1 million years is higher for a GDF set in a HSR than in a LSSR (peak risk $\sim 1.87 \times 10^{-7}$ yr^{-1} compared to 1.89×10^{-8} yr^{-1}), and the rate at which the risk emerges was faster. The peak annual radiological risk in this time frame has increased to less than an order of magnitude below the RGL, in fact the 95th percentile values for the peak risk in this scenario were as high as 2.43×10^{-7} yr^{-1}. Though only indicative, and making a number of assumptions that have not factored in the probability of occurrence in each setting (i.e. likelihood of all canisters being breached), it was noted that a GDF in a higher strength rock may pose a larger risk to those in the biosphere than one hosted in lower strength sedimentary rock. Much more sophisticated programmes of modelling, surface and site investigation will be required to determine if any one geological setting offers enough significant benefits to be considered the stand-out option, especially given the current policy position not to adopt a "best geology" approach [97].

5.6.5 Summary of Peak Annual Radiological Risks

The base case represented a baseline for analysis of the annual radiological risk arising from the disposal of the UK inventory of spent AGR fuel in a LSSR geological setting at a depth

of 500 m. The calculated peak risk of 2.36 x 10^{-8} yr^{-1} is approximately 0.4 % of the current regulatory recommended RGL for a GDF located in England or Wales. To assess the sensitivity of the base case result to uncertainties in some key parameters, a number of sensitivity studies were carried out as shown throughout 5.6.2.1-5.6.2.9.

The peak annual radiological risk for each of the sensitivity cases are shown in Figure 5.24. Errors have been estimated based upon the 5th and 95th percentiles for each set of realisations.

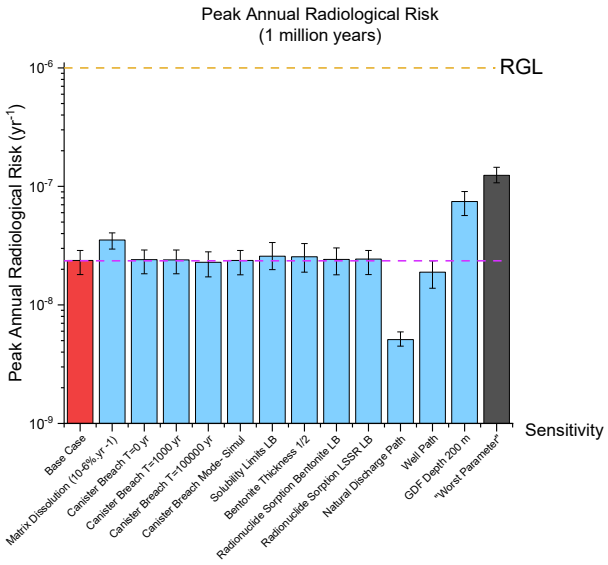


Figure 5.24: Peak Annual Radiological Risks obtained from Sensitivity Analysis.

Most notably, when accounting for uncertainties and errors, none of the sensitivities (individually or combined) amounted to an annual risk to PEGs in the biosphere within an order of magnitude of the RGL within the first million years post-closure. However, an increase in matrix dissolution rate was the only single sensitivity investigated which resulted in an increase in risk of more than 1×10^{-8} yr^{-1} when compared to the base case risk. This also dominated the risk profile generated for the worst parameter scenario's and associated peak radiological risk. This scenario exhibisted a peak annual radiological risk higher than the base case, though taking account of uncertainties associated with the worst parameter scenario, this value, within the first 1 million years post-closure, was still ~20 times lower than the RGL.

5.7 Implications for Regulation of a GDF and Future Work

This model simulated a GDF in which AGR SNF canisters were surrounded by a bentonite buffer, within a lower strength sedimentary rock (LSSR) geological setting, and overlying chalk layers. Its purpose was to indicatively quantify the risk to members of the public, resulting from the deposition of the UK's AGR inventory in the GDF. Typically, the recommended risk guidance level (RGL) deemed appropriate for nuclear activities is on the order of 10^{-6} yr^{-1}, or 1 in a million risk of death per year.

The results of the base scenario indicated that the annual risk to a member of a potentially exposed group, residing in the biosphere local to the GDF site was on the order of $\sim 2.36 \times 10^{-8}$ yr^{-1}, i.e. a 1 in 42 million chance of death per year due to radiological release from the GDF, and significantly lower than the RGL. A number of parameters were altered and simulated to identify which, if any, of the physical or chemical characteristics of the geological setting or engineered barrier system would incur significant alterations to the value of risk. These indicated however, that the predicted annual radiological risk was relatively insensitive to most of the parameter variations employed and that even those that impacted the risk the most did not result in risks within an order of magnitude of the RGL.

This models results are only indicative and suggest that none of the sensitivity studies investigated indicated a need for special regulatory attention, as the risk remains below the broadly acceptable range for each case. Even a scenario in which the highest-risk version of each parameter was employed resulted in a peak risk 1/6 of the magnitude of the RGL threshold value (1×10^{-6} yr^{-1}). These results may indicate that relative to higher risk nuclear installations, the regulatory oversight afforded to the GDFs operational and pre-closure safety might not need to be quite as stringent. Regulatory focus could then centre those aspects which are unique to geological disposal, such as challenges associated with demonstration of regulatory compliance in the underground workings of the GDF or the site boundary of the underground footprint (as discussed further in Chapter 8). However, it is important to appreciate the role that a diffusion

dominated geosphere might have played on the overall risk profiles generated throughout these studies. Restricting groundwater flow to diffusion outwith the EBS may have significantly masked the effect of the sensitivities within the EBS on the annual radiological risk. Therefore, future investigations may wish to consider the radiological flux at the interface between the EBS and the geosphere, particularly one that is diffusion dominated, and based upon this, whether the criteria for site selection should in any way be influenced by the availability of "best geologies".

The initial investigation utilising a different generic geological setting indicated that the peak annual risk associated with a GDF at the same depth located in a higher strength rock (HSR) was an order of magnitude larger than in an LSSR although still below the RGL. This again highlights the impact (on the annual risk) of the mechanism for groundwater flow. As regulator's do not make decisions as to the siting of the GDF, and the general approach taken in the UK towards siting is based on voluntarism and not one of selecting the "best geology", the level of regulatory oversight could vary depending upon the site selected for the GDF. For a GDF in a HSR geological setting, there could be a need for a larger regulatory oversight on processes related to the GDFs design, including scrutiny of safety submissions related to the EBS performance and the validation of the assumptions used in defining the geology. Although only significant work on engineered barrier performance in the HSR would confirm the extent to which disposal in the HSR rather than an LSSR would impact on post-closure safety.

Finally, this model considered release of radionuclides into a single, generic biosphere, which makes assumptions about the habits of PEGs and the risk posed by disposal, to them. These assumptions include the consumption or ingestion of materials contaminated by groundwater containing radionuclides. What this model does not consider, which future work may wish to, is the possibility that the immediate biosphere resides inshore for some or all of the post-closure period (e.g. for a GDF which is accessed from land but resides under the seabed). The factors utilised in the generation of biosphere dose conversion factors, which ultimately impact on risk, would be significantly different and would need to reflect PEGs with vastly different behaviours.

This level of modelling is suitably placed to provide an early indication as to whether sensitivities in the geological disposal process are likely to have significant effect on the radiological risks posed by disposal, given the regulatory development and decisions regarding the design, construction and operation that will follow the site-selection for the UK's GDF. However it should be remembered that in the generation of this model, a number of assumptions and simplifications were made. It is recognised that further work to better represent the GDF and its EBS using total system modelling, which would more accurately represent each feature of the repository, without as many assumptions or simplifications as utilised in this work. This could help build a more confident picture as to the effects of sensitivities and the choice of geological setting on the overall risk to the public, as well as establishing legitimate "worst-case" scenarios upon which regulatory scrutiny or analysis may be based.

More in-depth risk analysis is, or will be conducted in the development of GDFs and deep geological repositories (DGR) in a number of national programmes across the world. These will inform the licensee's arrangements under regulatory requirements by aiding safety arguments and submissions made throughout the GDF/DGRs lifecycle. Chapter 6 considers the regulation of nuclear safety for facilities at varying stages of development, in seven national programmes.

Chapter 6

Mapping the Regulatory Landscape: International Regulatory Frameworks for Geological Disposal

6.1 Introduction

The experience of national disposal programmes and the regulation of GDFs around the world will be beneficial in providing an insight into how an appropriate regulatory framework for a GDF located in England or Wales could be established. Chapter 6 summarises the regulatory approaches employed in a number of countries with geological disposal programmes, and key themes have been drawn out which might inform the regulatory framework for the UK's GDF.

In Chapter 7, the existing framework for the regulation of nuclear installations in the UK is described. This regulatory framework will in some form be applied to facilities for the disposal of higher activity waste (HAW), such as a geological disposal facility (GDF). Herein, the framework for regulating disposal in a number of countries is outlined, to gain an understanding as to what might need to be reflected in the existing UK framework for it to be applicable to the GDF.

6.2 International Requirements Applied to Geological Disposal

Most countries with civil nuclear power programmes, including the UK, are contracting parties to international treaties and conventions related to nuclear safety, security, third party liability and safeguards. Cooperation with other nations and the continuous development of international practices play an important role in shaping regulatory requirements, which are necessary to provide the international community with confidence that the proposed utilisation of nuclear energy will be conducted safely and responsibly.

6.2.1 Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management ("Joint Convention") was adopted in Vienna on 5th September 1995 [262]. The Joint Convention aimed to address the important area of the safety of spent nuclear fuel and radioactive waste, including disposal, which had been previously excluded from the Convention on Nuclear Safety (1994). Under the Joint Convention, it is clear that disposal is considered to be the definitive management option for radioactive waste. It places a number of requirements on contracting parties to establish legislative and regulatory frameworks specific to the governance of safety of spent fuel management and radioactive waste management to establish a regulatory body, and ensure the licence holder is primary responsible for the maintenance of safety on the licensed site.

6.2.2 IAEA Statute and Safety Standards

The International Atomic Energy Agency (IAEA) was established by statute in October 1956. Its principal objective is to "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world" [263]. The statute sets out the IAEA's

authority and responsibilities, including the obligation to establish or adopt standards of safety to minimise danger to life and property, and ensure the protection of health. It mandates the IAEA to aid the development of domestic legal arrangements for the regulation of nuclear energy and ionising radiation.

The IAEA published the Handbook on Nuclear Law to provide guidance on the technical and management requirements for a nuclear safety regulatory framework [264]. It discusses a number of principles relating to:

1. Safety
2. Security
3. Responsibility
4. Permission
5. Continuous control
6. Compensation
7. Sustainable development
8. Compliance
9. Independence
10. Transparency
11. International co-operation

The handbook also outlines the fundamental elements of an acceptable national framework, including the establishment of a regulatory body and its basic functions and the creation of a system for licensing, inspection and enforcement.

The IAEA's Safety Standards Series is made up of a collection of fundamental safety principles, general and specific safety requirements, and safety guides. The safety standards apply to the IAEA's own operations and are expected to be applied in Member States. The Fundamental Safety Principles reiterate the IAEA's primary safety objective, the protection of people and the environment from ionising radiation-induced harm [265]. Principle 7 "Protection of present and future generations" requires the operator to consider the consequences of present actions on current and future generations when assessing the adequacy of radiation risk control measures.

Specific to waste management, Principle 7 states "Radioactive waste must be managed in such a way as to avoid undue burden on future generations" ensuring waste generation is minimised and waste producers manage waste via safe, practicable and environmentally friendly methods. The IAEA's safety requirements documents are shown in Figure 6.1, and cover general requirements (GSRs) for nuclear safety including the role of government, legislation and regulation (GSR 1 Part 1) and the management of radioactive waste pre-disposal (GSR 1 Part 5). Requirements for specific activities (SSRs) including the safety of radioactive waste disposal facilities (SSR5) are also included.

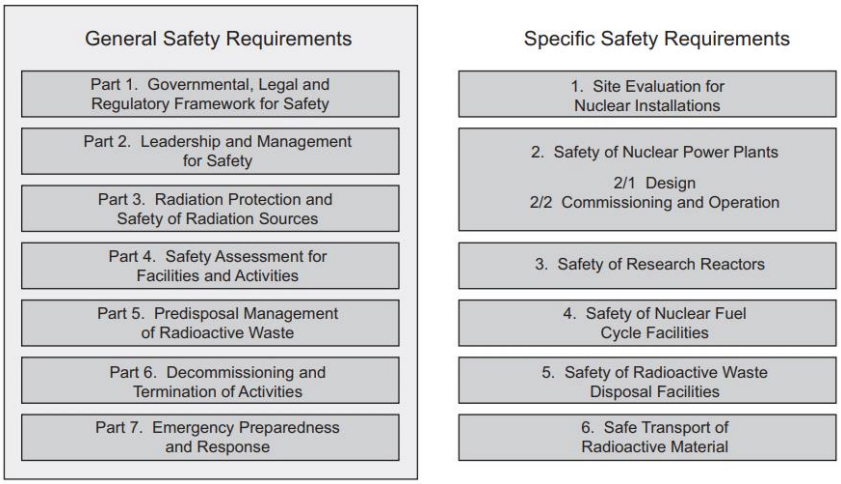


Figure 6.1: IAEA General and Specific Safety Requirement documents [18].

These documents are supported by guidance documents which present good practice; Specific

Safety Guide 14 (SSG-14) focuses on Geological Disposal Facilities for Radioactive Waste [64].

6.2.3 European Council Directives

The European Union established a number of Directives relating to radioactive waste management that mirror the requirements of the Joint Convention. European Council Directive 2011/70 Euratom states: "Deep geological disposal represents the safest and most sustainable option as the end point of the management of high-level waste and spent fuel considered as waste." [266]. Also pertinent is the EU Impact Assessment Directive (Council Directive 2011/92/EU), which aims to ensure that projects deemed likely to have a significant impact on the environment are identified, assessed and publicly consulted on before they can proceed to development [267].The UK's withdrawal from the European Union and Euratom Treaty means that obligations contained within EC Directives will no longer apply to the UK, however the overarching principles will still be relevant to the development of the UK's regulatory approach and the UK has already implemented these in domestic legislation. The majority of Euratom legislation was developed to aid the implementation of international legislation and conventions, which the UK is party to, as such the laws as implemented in the UK remain relevant.

6.2.4 WENRA Safety Reference Levels

The Safety Reference Levels (SRLs) including those relating to the management of radioactive waste, developed by the Western European Nuclear Regulators' Association (WENRA) are considered as relevant standards of good practice for UK radioactive waste management, including disposal [268]. The WENRA SRLs were explicitly considered throughout the development of the ONR's technical assessment guides (TAG), with the ONR committed to transposing relevant SRLs into TAGs for disposal [269], [270]. The SRLs provide safety requirements specific to specialised radioactive disposal facilities, focusing on licensee responsibilities from pre-licensing until GDF closure [266]. The reference levels are goal setting and provide guidance on site

characterisation, design, construction, operation and closure of a GDF.

6.2.5 Third-party Liability

The UK is a member of the Organisation for Economic Co-operation and Development (OECD), and is a contracting party to the Paris Convention on Third Party Liability in the Field of Nuclear Energy and the Supplementary Convention to the Paris Convention ("Brussels Supplementary Convention") [271], [272]. These Conventions were established to provide a means of enabling growth in the nuclear industry without liability issues hindering progress. They cover compensation in the event of a nuclear accident that causes injury or loss of life, damage or loss of property. Under the amended Paris-Brussels Convention, the operator of a nuclear installation, including radioactive waste disposal facilities, is liable for accidents at the installation or during transport of nuclear substances [273].

The obligations of the Paris-Brussels Convention are implemented through the Nuclear Installations Act 1965 (NIA65) [12]. For example a licensee must be able to demonstrate it has sufficient funds to cover the liability up to the limits set out in the NIA. The Nuclear Installations (Liability for Damage) Order 2016 amended the NIA, increasing the amount of compensation and pool of potential claimants in the event of a nuclear incident; this was prompted by the 2004 protocol amending the provisions of the Paris Convention which brought both the operational and post-operational phases of a GDF into the scope of the convention [273], [274]. The UK Government considers that the liability regime set out in the convention should only apply to waste disposal facilities that present a level of risk that the Paris Convention was designed to cover, and are seeking to exclude disposal facilities which dispose of low- and very low-level radioactive waste under article 1(b) of the Paris Convention. At present these are prescribed under The Nuclear Installations (Prescribed Sites and Transport) Regulations 2018 for the purposes of section 16(1)(b) of the NIA65 which considers liability [275]. The risk analysis of geological disposal presented in Chapter 5 indicated the risk to members of potentially exposed groups (PEGs), living in the locality of the GDF site, will remain sufficiently below recommended

levels [237]. The significant amount of engineering that will be employed to ensure hazard potential, and inherently the level of risk, remains low might indicate these exclusions could be extended to the regulation of a GDF. As the 2004 amendment explicitly applies to the GDF, it may instead be that the Government seek to classify the GDF as a low or intermediate risk site to justify a lower level of financial security being required.

6.2.6 Nuclear Non-Proliferation Safeguards

The UK, as one of the five nuclear weapons states, maintains a voluntary offer agreement (VOA) and additional protocol with the IAEA regarding its safeguards arrangements, as outlined in 7.1, implemented under the Nuclear Safeguards Act 2000 [276]. The GDF would qualify as a facility to which these safeguards regulations apply, once in receipt of at least one effective kilogram of nuclear material (for which safeguards have not been terminated) [277].

6.3 International Legislation and Regulation for Geological Disposal Facilities

A number of countries are committed to the disposal of radioactive waste or spent nuclear fuel via geological disposal. Some countries, such as Finland and Sweden, have already identified sites and commenced construction whilst other such as the UK are actively engaged in the siting process. The experiences of these countries will be valuable in later (Chapter 8) assessing the UK's regulatory framework against international best practice, given these nations will each be required to comply with the same standards as the UK.

6.3.1 Regulating Geological Disposal in: Finland

Finland's GDF is intended for the disposal of spent nuclear fuel, and excavation has commenced on the final disposal tunnels at the Onkalo repository [8]. The regulatory framework for the disposal of spent fuel, from design through to GDF closure, is therefore well established.

6.3.1.1 Legislation

There are three primary legislative instruments that govern nuclear activities in Finland, which are supported by secondary tools such as decrees, ordinances and rules. The Nuclear Energy Act 1987 (NEA87), which replaced the earlier Atomic Energy Act of the 1950s, established the basic governing principles for the regulation of nuclear energy in Finland [278]. It clearly defines which activities are considered "uses" of nuclear energy, licensing requirements, the responsibilities of involved parties and how the use of nuclear energy should only be for the overall good of society. The act also states that waste generated in Finland must be handled, stored and disposed of in Finland and requires waste disposal activities to be licensed. Provisions specific to nuclear waste management are set out throughout chapters 6 and 7 of the NEA87, upon which the regulatory framework for waste management in Finland is built.

The "Radiation and Nuclear Safety Authority Regulations on the Safety of Disposal of Nuclear Waste" (Y/4/2018) were adopted and issued in December 2018 as a revision of the previous Government Decree of 2008 [279]. They provide specific requirements for the handling, storage and disposal of spent nuclear fuel, including the formulation of a safety case, demonstrating compliance with safety requirements and limitations on radiation exposure and release.

The Radiation Protection Act (2018) (RPA18) regulates activities that cause or may cause exposure to radiation [280]. Regulatory controls include justification of practices, application of the as-low-as-reasonably-achievable (ALARA) principle and individual dose limitations.

Finally, the Nuclear Liability Act (1972) covers Finland's liabilities in the event of damage

caused by its nuclear industry and ensures that the liability from such events lies with the Finnish operator [281].

6.3.1.2 Organisations Involved in Waste Management

The delivery body for the disposal of radioactive waste in Finland are Posiva, founded in 1995 by two Finnish nuclear plant operators Teollisuuden Voima (TVO) and Fortum. They commenced construction on the Onkalo site in 2004, focussing on the large access tunnel to the facility. A construction licence for the disposal facility's repository was granted in 2015.

The NEA87 established the authorities responsible for the management and regulation of nuclear energy (including waste management) in Finland. The competent authority for the oversight of nuclear energy (including radioactive waste management) in Finland is the Ministry of Economic Affairs and Employment (MEAE).

The Radiation and Nuclear Safety Authority (STUK) is the regulatory body for radioactive waste management including GDFs, falling administratively under the Ministry of Social Affairs and Health. STUK is also responsible for the regulation of security, emergency arrangements and non-proliferation safeguards. STUK plays a major role in the licensing of nuclear facilities, including processing of licence applications, development of legally binding regulations and enforcement/compliance activities such as site inspections and approval or practices. STUK provides licensees with administrative procedures in the form of "YVL" (regulatory guides on nuclear safety), on matters including nuclear and radiological safety, plant design and nuclear materials and waste, including YVL D.5 on the "Disposal of Nuclear Waste" [282]. STUK is assisted by advisory commissions on matters concerning the safety and security (see Figure 6.2).

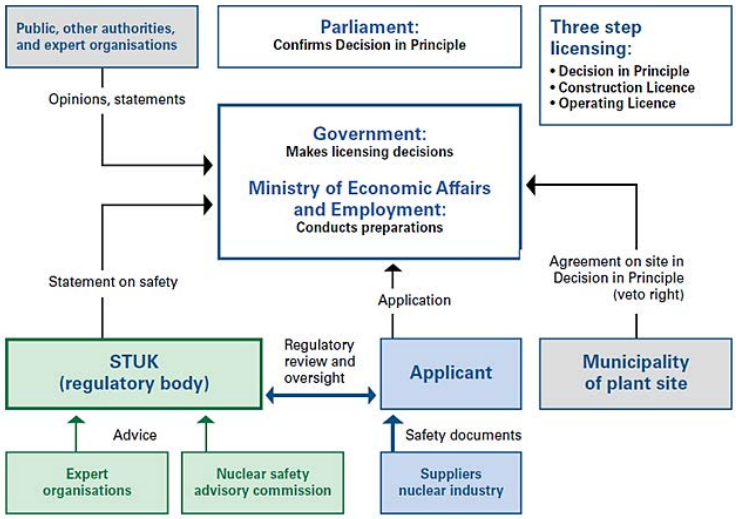


Figure 6.2: Bodies involved in the authorisation of nuclear installations in Finland. Adapted from [283].

The Finnish Parliament are responsible for granting a decision in principle as part of the licensing process, whilst the Government are responsible for final licensing decisions (see 6.3.1.3).

6.3.1.3 Licensing and Permitting

As required under the Joint Convention, a licensing regime is being applied to the Finnish geological disposal programme. The developer is required to undertake an environmental impact assessment (EIA), in which the potential effects on the environment must be evaluated as part of the decision making phase of the project, prior to the licence application process. The process for assessing environmental impact begins with the generation of an environmental assessment programme which is submitted to the MEAE and consulted on in the host and neighbouring municipalities. As the coordinating authority, the MEAE provide a statement on the programme. Only then, can the developer put together the EIA, which is subjected to further public hearings and resolved by a "reasoned conclusion" by the MEAE.

Once the EIA has been ratified, applicants are subject to a four-step licensing process, comprising:

1. Decision in Principle- conducted by Government, ratified by Parliament.
2. Application for Construction Licence by Licensee- granted by Government
3. Application for Operational Licence by Licensee- granted by Government
4. Application for Decommissioning Licence by Licensee- granted by Government

The decision in principle process is defined within chapter 4 of the NEA87, and to be granted, it requires the project must be in line with the "overall good of society". The applicant must produce a report detailing the specifics of the proposed facility, activities environmental and safety considerations, upon which the MEAE is tasked with organising consultations with the public, residents and municipalities and local authorities. The Government may then grant a decision in principle, attaching conditions as necessary in the interest of nuclear safety, usually for a fixed 5-year term, to which no changes to the decision or the application can be made.

In order for the operator to obtain a construction licence, a written application is made to the MEAE including justifications, costing, supply chain, planning and expertise important to safety, along with preliminary plans for security, emergency and safeguards arrangements. Once a construction licence has been granted, STUK take control over the regulation of the project.

For an operating licence to be granted, the operator must submit a final safety analysis report and probabilistic risk assessment along with technical specifications and programmes for periodic inspections and environmental radiation monitoring. An operating licence is granted when STUK is satisfied that the facility meets all relevant safety, security, emergency arrangements, non-proliferation and liability requirements.

A decommissioning licence will be required as part of the decommissioning and closure phase of Finland's GDF. This step was introduced as part of proposals to revise the NEA87, removing decommissioning from the operating licence regime, instead requiring the licensee obtains a decommissioning licence to cease operations and move the facility into a phase of decommissioning. To be granted, STUK require assurances as to the adequacy of the operator's decommissioning

methods, decommissioning expertise and the adequacy of the financial and other resources required to carry out full-scale decommissioning and closure of the site.

Before the repository is allowed to close, the safety case will need to be updated by the licence holder for review by STUK. This should demonstrate that the disposal facility has been designed, constructed and operated in a manner that allows it to be closed without compromising long term safety, and to maintain favourable characteristics of the host rock, as far as is possible [279].

The operator shall also submit for approval a closure plan to STUK prior to final closure, which details closure principles, preliminary design requirements, implementation plan potential future institutional control measures. An initial closure plan for the repository was presented in the construction license application and in in 2012. Posiva will continue the detailed closure planning over the forthcoming years. Under NEA Section 34, once final closure has been approved, the state bears responsibility for future waste management incurred costs [278]. At this point, regulations dictate that records must be kept of the disposed waste, including waste package specific information (i.e. waste type, radioactive substances, emplacement locations etc.) [279].

Post-closure monitoring is not expected to be required or implemented to due the passive safety associated with the design of the Finnish repository. Nonetheless, NEA Section 63 provides STUK with a number of rights regarding post-closure regulatory oversight, which include the issuance of land use restrictions [278]. Regulations support the rights set out in Section 63 by requiring the licensee (as part of the closure plan) to provide a proposal for a "protection zone", reserved for the post-closure period [279].

6.3.2 Regulating Geological Disposal in: Sweden

In 2009, a site was selected for a spent fuel repository at Forsmark, in the Östhammar municipality on Sweden's east coast. The developers hope to commence initial construction activities on the site, close to the Forsmark nuclear power plant, in the early 2020s; applications were made to

the regulator and environmental court to commence construction in 2011.

6.3.2.1 Legislation

The legislative framework for the regulation of geological disposal in Sweden is made up of a number of acts and ordinances, with remits related to nuclear safety, radiation protection and environmental protection.

The Act on Nuclear Activities (1984; "ANA84") provides the legislative foundation for the regulation of nuclear safety in Sweden [284]. The act defines spent nuclear fuel placed in a repository as nuclear waste, and stipulates the disposal of spent nuclear fuel or nuclear waste is prohibited without a specific licence. The act sets out licensee and authority responsibilities, and requires a prospective licensee to include an Environmental Impact Assessment (EIA) as part of the application for a licence for the construction, possession on (of nuclear material) or operation of prescribed facilities. Detailed provisions for the regulation of nuclear safety, are set out in The Ordinance with instructions for the Swedish Radiation Safety Authority [285].

The Act on Radiation Protection (2018; "ARP18") outlines the requirements for protection of people, animals and the environment against the effects of ionising or non-ionising radiation [286]. It also places a licensing requirement on ionising radiation activities, including disposal of radioactive substances, unless a facility is already licensed under the ANA84. The ARP18 requires those conducting activities involving ionizing radiation to ensure radioactive waste arising from specified activities is handled and where necessary, disposed of as soon as reasonably possible. The act is enforced in line with International Commission on Radiological Protection's (ICRP) principles of justification, optimisation and dose limitation [251].

The Environmental Code (1998) (TEC98) governs sustainable environmental development, and a healthy environment for current and future generations [287]. Geological disposal of radioactive waste is defined an environmentally hazardous activity for which a licence is required under to the ANA84 or RPA18, and under the TEC98. The code also stipulates the requirement for an

EIA, to form the basis of the licensing programme.

The regulatory framework for geological disposal in Sweden is made up of binding safety and radiation protection regulations, legally mandated and issued by the regulator, under their Regulatory Code (SSMFS 2008:51) [288]. Those specific to the disposal of SNF and radioactive waste include the "Regulations concerning safety in connection with the disposal of nuclear material and nuclear waste" (SSMFS 2008:21) and the "Regulations and general advice on the protection of human health and the environment in connection with the final management of spent nuclear fuel and nuclear waste" (SSMFS 2008:37) [288], [289].

6.3.2.2 Organisations Involved in Waste Management

The Swedish Nuclear Fuel and Waste Management Company (SKB) are the delivery body for the management and disposal of all radioactive waste from Swedish NPPs. This includes delivery of Sweden's Spent Fuel Repository, from siting through to decommissioning and closure.

The Swedish Radiation Safety Authority (SSM) are designated the regulatory body for the supervision of spent fuel and radioactive waste management, under the ANA84 and RPA18. They are an independent administrative authority, supported by the Ministry of the Environment and Energy, who actively promote high levels of nuclear safety, radiation protection and non-proliferation, as outlined in the Ordinance with Instructions for the Swedish Radiation Safety Authority (2008:452). Their activity includes the operation of a national dose register, acting on international obligations, developing national competence and communication of regulatory activities.

SSM are not responsible for the granting of licences under the ANA84 and TEC98, though are permitted to attach licence conditions to a licence under the ANA84 and issue general regulations in the interest of maintaining the safety of nuclear activities [290]. The Swedish Land and Environment Court are responsible for scrutiny of licence applications under the TEC98 for permissibility, and attaching conditions in the interest of environmental safety. Final

licensing decisions in both instances are taken by the Swedish Government (see 6.3.2.3).

6.3.2.3 Licensing and Permitting

The Swedish system for licensing involves a number of parties, including the delivery body, SKB, the regulator, SSM, the Land and Environment Court and local and regional government, displayed in Figure 6.3.

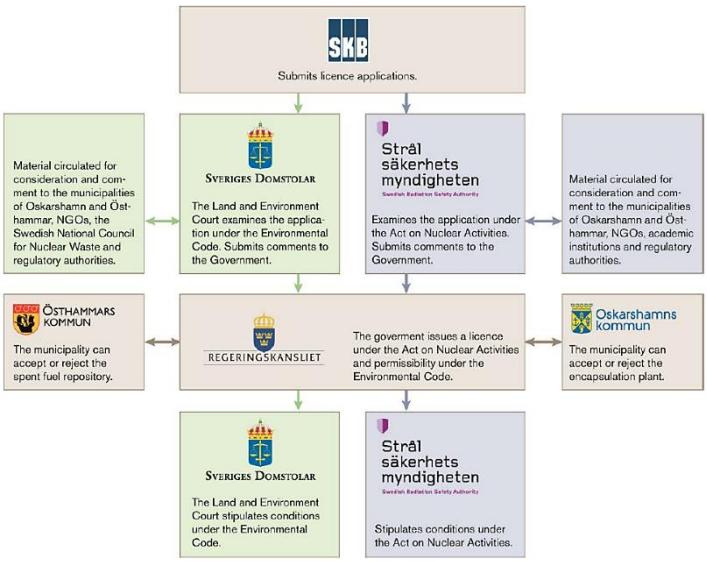


Figure 6.3: The process for licensing a spent nuclear fuel repository and encapsulation plant in Sweden [290].

The operator must make an application for environmental permissibility, under the TEC98, and nuclear safety, for a licence under the ANA84. As part of the application, an environmental impact assessment (EIA) is required, which is consulted on with affected parties including local environmental and public health committees, and heard at a public hearing. The EIA is required to establish the direct and indirect effects of a planned activity on aspects of the natural world detail the activity, actions for avoiding or mitigating environmental impacts and the potential impacts on human health, the environment and land management.

The application for an environmental licence is considered by the Land and Environment Court

The permissibility of the activity is assessed in an open hearing, after which the court inform the Government who may issue permissibility, allowing the Land and Environment Court to grant a permit under the Environmental Code, attaching any conditions they deem necessary in the interest of environmental protection.

In the application for a licence under the ANA84, the operator is expected to submit a first/preliminary safety analysis report (F-PSAR), which includes information related to the site, design, construction and safety assessments and operator capability in accident or incident mitigation. The application should also cover aspects of compliance with Chapter 2 of the TEC98 ("General rules of consideration") and information related to planned emissions or releases, physical protection, emergency preparedness and organisational competency.

The application is submitted to the regulator (SSM) who examine it and provide local organisations (municipalities, NGOs, academic institutions and local regulatory authorities) with the application dossier for further inspection as well as to Scandinavian sister organisations. In accordance with Article 37 of the Euratom Treaty, they must also forward relevant data to the European Commission.

Information gathered from these organisations and their own examination form the basis for SSM's review of the application under the ANA. The review includes a recommendation as to whether the government should grant the licence, and conditions which should be attached in the interest of safety. For a disposal facility, such conditions may include the requirement for SSM approval prior construction, trial or full-scale operations. Government will then make a licensing decision for the construction of the GDF, and subsequently for trial and routine operations and closure of the disposal facility, as in Figure 6.4.

Prior to closure of the disposal facility, the final safety assessment must be updated and approved by the regulator (SSM) [290]. Following this review, the Government will decide whether final closure can commence, following which the licence holder may be relieved from its responsibilities and obligations (though at present requirements for institutional control after the repository

has closed has yet to be formally decided). Any future intervention measures required following the revocation of the licence therefore fall to the State.

Under the regulations on information archiving at nuclear facilities (SSMFS 2008:38) [291] there are requirements for record management, which stipulate that certain documents concerning location, design and inventory of the waste disposed of must be kept in archives for more than 100 years. Onus is placed upon the licence holder to develop and manage records, and general guidance from suggests this should be established prior to facility closure.

Closure of the Swedish repository will be a stepwise process, closing a deposition tunnels first, followed by closing one or multiple deposition areas until the whole repository is closed. Monitoring implemented throughout the operational phase will continue until all waste has been emplaced and closure of the repository facility is commenced. During closure, monitoring systems accessible only from underground will be decommissioned. Several regulations [288], [289], [292] related to safety in nuclear installations, in connection with the disposal of nuclear material and nuclear waste and for the protection of human health and the environment of spent nuclear fuel and nuclear waste stipulate post-closure safety shall be maintained through a system of passive barriers and should not rely on the implementation of active measures. As such, it is not expected that post-closure surveillance or monitoring will be required, though it is anticipated that decisions around this will be made shortly before closure.

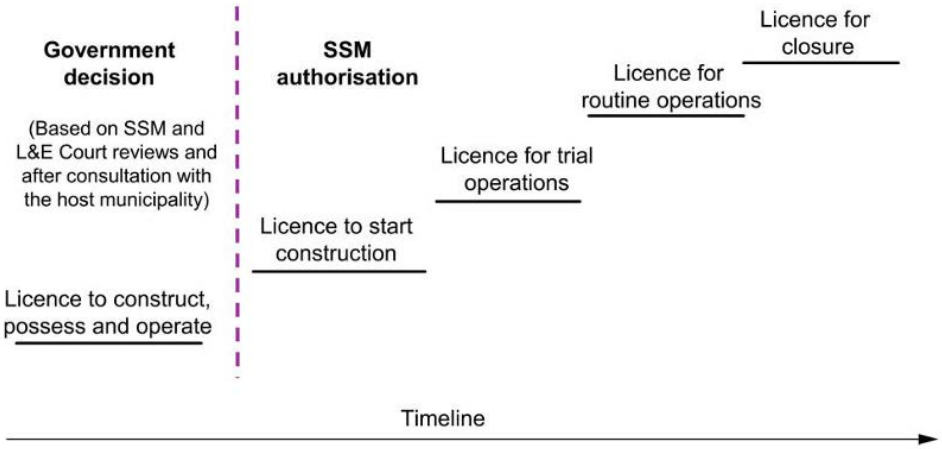


Figure 6.4: The stepwise regulatory authorisation and supervision for licensing in Sweden [290].

6.3.3 Regulating Geological Disposal in: France

In 2006 geological disposal was deemed the most suitable solution for the permanent disposal of France's hazardous radioactive waste. The surface site of Cigeo (Centre Industriel de Stockage Geologique) will be split between two areas in the Meuse and Haute-Marne departments of Eastern France, where research and consultation have been active for over 20 years. The overhaul of the legal system for nuclear installations in France has shaped the framework for radioactive waste management, in keeping with international best practice.

6.3.3.1 Legislation

Nuclear installations are classified in accordance with a threshold set out in Decree No. 2007-830, above which all facilities are regarded as Basic Nuclear Installations (BNIs) [293]. This includes facilities "whose main purpose is to manage radioactive waste", such as a deep geological repository (DGR).

The BNI Licensing and regulatory system is underpinned by the Environment Code (EC) (Chapters I, III, V and VI of title IX, Book V). The EC provides an integrated system

for legislation that encompasses nuclear safety, security and environmental protection. The regulations applicable to BNIs are based on the EC and its associated decrees. The codification of three acts provided the basis for the regulatory framework of geological disposal in France.

The Act 2006-686 on transparency and security in the nuclear field ("TSN Act") led legislative revisions applicable to BNIs and forms Title XI of Book V of the EC (L593-1 to L593-43) [294]. The TSN Act is the legislative base for the governance of nuclear safety in France. The provisions of the act include the creation of France's Nuclear Safety Authority "Autorité de sûreté nucléaire" (ASN) and rules applying to BNIs. Enforcement decrees and ministerial orders set regulatory expectations for nuclear installations, including the Order of 7 February 2012, which outlines general technical requirements, rules and guidelines for basic nuclear installations ("BNI Order") [295]. Title VI "Waste Management" applies to radioactive waste disposal, licensee responsibility and waste acceptance criteria.

The decree 2007-1557 relative to basic nuclear installations and oversight of the transport of radioactive substances from the nuclear safety aspect ("BNI procedures" decree) acts as the decree for the enforcement of parts of the EC [296]. Informed by the TSN Act, it includes "the conditions of application of the law" for the authorisation of the creation and development of a BNI, setting out the procedure and prerequisites for the licensing of a BNI.

The Programme Act 2006-739 of 28th June 2006 on the sustainable management of radioactive materials and waste ("Waste Act"; Chapter II of Title IV, Book V of EC) forms the basis of national policy on the management of radioactive waste [297]. The Waste Act provides special provisions for sustainable radioactive waste management, including disposal, whilst managing human health, safety and the environment. It defines radioactive waste as "consisting of radioactive substances for which no subsequent use is planned of envisaged" and waste that is impossible to process under the present technical or economic conditions as "ultimate radioactive waste". Article L542-10-1 sets out the regulatory framework for the authorisation of a Deep Geological Repository (DGR), establishing obligations for disposal "reversibility", and the implementation of a licensing procedure (see 6.3.3.3).

The Act 68-943 of 30th October 1968 on civil liability in the nuclear energy field ("RCN" Act) formalises the licensee's responsibility for civil liability, pursuant to the Paris and Brussels Conventions [298].

The Public Health Code (CSP) further prescribes "nuclear activities", as all activities involving a personal exposure risk due to ionising radiation from an artificial or natural source, establishing the Radiation Protection Inspectorate (RPI), responsible for controlling the application of radiation protection mitigation [299].

The French regulatory framework provides operators with a series of Basic Safety Guides which define safety objectives and practices that would ensure compliance with the regulatory expectations.

6.3.3.2 Organisations Involved in Waste Management

The French national radioactive waste management agency, Andra, are responsible for identifying and implementing the safe, long-term management of radioactive waste in France, including disposal in the DGR.

ASN is an independent administrative body providing regulatory oversight, opinion and clarification on matters of nuclear safety and security. The ASN are statutorily required to supervise operator compliance with regulatory requirements at all stages from DGR design through to shutdown. ASN maintain control through annual inspection programmes and the assessment of technical documents put forth by the operator during licensing applications and throughout the lifecycle of a BNI. ASN is not responsible for the administering authorisation or licences to applicants/operators; permissioning (including licensing) is the responsibility of French Government (see 6.3.3.3).

The RPI is responsible the implementation of radiation protection provisions on the licensed site, set out under the Public Health Code, which was composed in accordance with international standards.

6.3.3.3 Licensing and Permitting

The process for licensing and safety submissions is outlined in the BNI Procedures Decree ("the decree"). The decree sets out a step-wise licensing process for a DGR includes:

1. Public Debate
2. Safety Assessment
3. Other preliminary documents
4. Creation Licence application
5. Commissioning Licence
6. Final Shutdown
7. Post-closure monitoring

Prior to the submission of an application for a creation licence, which enables the creation and construction of a Basic Nuclear Installation, prospective operators are encouraged to seek the opinion and insight of the ASN on matters of nuclear safety and conduct public debate(s) centred on the project.

The creation licence application, outlined in Articles 7-17 of the decree, commences when an application is put to the Minister responsible for nuclear safety, submitted alongside a number of documents, including an environmental impact study (EIS), preliminary safety analysis report (PSAR), risk management study (RMS), and detailed plans of the facility and of its proposed final shutdown.

The EIS details factors that could directly or indirectly effect human health and population, and a host of environmental including biodiversity and water, air and climate. Environmental protection submissions will be scrutinised by the Environmental Authority (General Council for the Environment and Sustainable Development). The PSAR, outlines perceived risks arising

from the proposal and an analysis and management plan for the mitigation of accidents. The RMS provides information regarding the potential risks posed by the development and the measures to be implemented to ensure they are minimised.

The ASN, provide a technical analysis of the application whilst the RMS and EIS are put forward for public consultation in local communities. The ASN submit their proposals to the Minister, where a final decision is made as to whether or not a creation authorisation decree (DAC) is suitable for the proposal. This may lead to the presentation of a draft DAC to the operator, who has 2 months to present its own comments. Meanwhile the ASN provide the Minister with advice on aspects including design, construction and operating requirements. A licence for the creation, including construction, of the DGR may be issued by the signing of the DAC, by both the Prime Minister and Minister responsible for nuclear safety.

In order to progress with active commissioning (the first utilisation of radioactive materials) the licensee must provide an updated version of the preliminary safety case, operating rules, on-site emergency plan and waste-management study to the ASN. The safety case must include data that demonstrates compliance with the requirements set out in the DAC and construction requirements set out in article 18 of the decree. Provided submissions meet the objectives and rules of the TSN ACT, the ASN are permitted to authorise in part or full, a licence for the commissioning of the site. These documents must be updated periodically throughout operation. In granting a commissioning licence, the regulator will specify a timeframe within which the operator must provide plans for the end of installation start-up.

The framework relative to the post-closure period is governed by Article L.593-31 of the Environment Code, which states that the facility will be considered for shutdown ("cessation of operation") as soon as the final batch of waste is deposited, and by regulation, once a BNI is definitely shutdown, it must be decommissioned. The licensee must make an application to the minister for the authorisation of facility shutdown and for transition into a phase of surveillance. This requires updated versions of documents submitted previously, including a detailed site plan, EIA detailing the state of the environment before and after shutdown, a post-shut down safety

case and RMS. Supervision rules replace operating rules, and include any public protection restrictions to be placed upon the site post-shutdown. The ASN are provided with a copy of the application, and a notice which demonstrates the operator's technical capabilities, financial capacity and step-by-step plan for the implementation of shutdown and surveillance. Following consultation, as in the creation authorisation process, a decree for the authorisation of shutdown ("decommissioning decree) may be granted by the Minister. The decommissioning decree modifies the creation authorisation decree by revoking provisions related to operation of the facility and prescribing decommissioning operations (including essentials aspects specific to maintenance of public health and safety, protection of nature and the environment). The BNI order stipulates these aspects must be maintained passively and not require human intervention beyond the limited monitoring and surveillance period [295].

6.3.4 Regulating Geological Disposal in: Germany

Germany is in the midst of its site selection process for a deep geological repository. Until 2012, Gorleben's salt dome was the only site considered feasible; it's now anticipated a final decision on the site for the repository won't be made until 2031. The regulatory framework has already been set out to accommodate facilities for the disposal of radioactive waste.

6.3.4.1 Legislation

In Germany, the Basic Law ("GG") establishes principles for democratic social order, the protection of life, health and natural resources. The separation of powers, independence of licensing/supervisory authorities and the supervision of administration by independent courts are also established [300].

The GG contains provisions related to the legislative and administrative powers of the Federation and Lander (federal states) with respect to nuclear energy. Under the GG, the Federation owns the legislative power for the production and use of nuclear energy for peaceful purposes, including

the construction and operation of facilities. Their remit extends to protection against the hazards arising or associated with ionising radiation, and for disposal of radioactive substances.

Enacted in 1959, the Atomic Energy Act (1959; “AtG”) lays out provisions for the protection of life, health and property against the associated hazards, both safety and security related, of nuclear energy and ionising radiation [301]. The AtG stipulates the requirement for the licensing or plan approval of a number of nuclear activities including the disposal of radioactive waste. For facilities for the management of spent fuel, the AtG outlines general protection goals for which broad licensing conditions have been generated. Where the location of a site for disposal has been decided by federal law, a licence replaces the requirement for "plan approval". The AtG places much of the financial onus of disposal on the waste producer.

Statutory ordinances provide in-depth instruction on issues related to geological disposal and the regulation of nuclear safety and radiation protection.

The Ordinance on Protection against the Harmful Effects of Ionizing Radiation (Radiation Protection Ordinance; "StrlSchV") sets out standards for radiation protection in the workplace, medical settings and for the protection of the population, supported by the 2018 Radiation Protection Act (StrlSchG) [302], [303]. The Nuclear Licensing Procedure Ordinance (AtVfV) stipulates the nature and content of documentation to be submitted as part of a licensing application, whilst the Nuclear Waste Shipment Ordinance (AtAV) regulates the transboundary movement of spent nuclear fuel through, to or from Germany [304], [305].

The Act on the Search and Selection of a Site for a Repository for Heat-Generating Radioactive Waste and for the Amendment of Other Laws (“Repository Site Selection Act”, StandAG) regulates Germany’s comparative site selection process for the repository intended disposal of high-level radioactive waste, outlining principles of public participation and the process flow, criteria and requirements for the repository’s site selection [306].

The Law on the Establishment of a Federal Office for Nuclear Waste Management (BfkEG) established an authority (on behalf of the Federation) who will conduct administrative tasks

related to the licensing of facilities for the safekeeping and disposal of radioactive waste pursuant to the AtG [307].

6.3.4.2 Organisations Involved in Waste Management

Under the joint convention, the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), are responsible for ensuring that those in charge of proposed applicants and operators, federal and Land authorities and authorised experts are capable of delivering high standards of human and environmental protection against the hazards of nuclear energy and ionising radiation.

The responsibility for licensing and supervision of the repository and nuclear fuel storage facilities is that of the Federal Office for the Safety of Nuclear Waste Management (BfE). Established in 2013 under the act which founded the BfE, the BfE perform regulatory, licensing and supervisory tasks on behalf of Federal Government, providing technical support to the BMUB on issues related to nuclear safety and disposal, including the regulation of site selection. Their remit extends to the application of mining and water laws and licensing, and licences for the transport of nuclear fuel/large sources.

Under the AtG, the Federal office for Radiation Protection (BfS) are responsible for the setting up and maintenance of registers detailing occupation radiation exposures, ethics commissions and high-activity radioactive sources in Germany [301]. The Land Ministry are responsible for the licensing and supervision of the construction and operation of spent fuel management facilities, and subordinate land authorities may be delegated (by the Land Ministry) to oversee the licensing and supervision of some waste management facilities.

6.3.4.3 Licensing and Permitting

German nuclear and radiation protection law places separate licensing obligations on specific activities, including facilities for the safekeeping and disposal of radioactive waste, which are

required under Article 9a of AtG. Should the handling of nuclear waste or fuel not be covered by any of the licences above, it must be licensed under the StrlSchV.

If a site is selected under Federal Law, the plan approval required under 9b is substituted by a licence under AtG Article 7 and the AtVfV. The AtVfV licensing process begins when the prospective operator submits their licence application to the competent licensing authority, which is BfE for the repository [308]. In accordance with AtVfV Article 3, this must be accompanied by a dossier which includes a safety analysis report, site and component plans, safety specifications, schedules and measures to be taken in the event of incidents or damage and data related to the project's environmental impact, including and environmental impact assessment (EIA).

The submission of an EIA with application documents allows for the impacts on all environmental aspects of the project to be analysed; this is regulated and enforced under the Environmental Impact Assessment Act (UVPG). The EIA should include a site description and design, information related to the type and quality of emissions, and measures for prevention and mitigation of environmental damage, and justifications of the technologies proposed.

If plans do not highlight any conflict with public welfare, and all licensing prerequisites have been met, submissions are subject to examination by authorities whose jurisdiction may be affected by the licensing process, including those in areas of civil engineering, water, and regional planning. The BMUB consult with advisory bodies who provide independent, expert technical advice on procedures, plans and regulations. They present their statement to the licensing authority (BfE), who conduct consultative activities and provide public access to application documents. Following consultation, reports from the BMUB and local authority input, BfE will make their licensing decision.

In the case where the site for disposal has not been designated by Federal Government, the plan approval process is enforced for the construction, operation, and decommissioning of a GDF, under AtG Article 9b. This bands all areas of relevant law into a single procedure and may progress in a step-by-step manner, requiring partial plan approval at each stage of the GDF's

development. This is governed under the Administrative Procedures Act (VwVfG), which sets out provisions for the staging of a public hearing, decision making by the competent authority, the legal obligations of planning approval and amendments/revocations of planning approval.

Under the plan approval process, the operator is required to submit plans to BfE hearing authorities, who gather the opinions of the relevant competent authorities, and make them available to the communities likely to be affected by the project. Interested parties can lodge objections for discussion at a public hearing, after which BfE (the planning authority) make their final consideration and planning approval decision.

By granting planning approval, the project is established as admissible, having been assessed across a breadth of relevant laws and licences including those under legislation relevant to building and nature conservation. No further administrative decisions are required once approval has been granted (AtG 9b), aside from mining and water laws [301].

A further plan approval decision under the AtG will need to be obtained by the operator when they wish to close the repository and enter decommissioning (at present there are no examples of this having occurred in Germany). A decommissioning plan compliant with radiation protection regulations must be in place which outlines the disposal concept. Under the Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste ("BMU 10") and the Radiation Protection Ordinance (StrlSchV), this must be reviewed and updated in accordance with the state of the art throughout the life cycle of the repository (through a ten-yearly review of safety reviews) [302], [309].

Under the Site Selection Act any documents that may become important to the storage or disposal of radioactive waste must be permanently stored by the Federal Office for the Safety of Nuclear Waste Management, and under BMU 10 it is required that a binding agreement concerning the scope, preservation and accessibility of documentation to be retained will be adopted after consultation with the licensing authority [306]. Following decommissioning, but prior to completion of repository sealing, it will need to be established what control measures

(if any) are to be required post-closure and by whom they shall be carried out. Administrative measures will also be put into place to ensure no human activities in the vicinity of the disposal facility could endanger the permanent containment of the waste.

6.3.5 Regulating Geological Disposal in: Switzerland

Under Swiss legislation, radioactive waste must be disposed of in a deep geological repository. The siting process is ongoing, with three sites shortlisted for further investigation. Based on the current timetable, a decision will be made by 2022, and by 2029 the licensing process will have commenced. As such the regulatory framework has already been adapted for the licensing of a disposal facility in Switzerland.

6.3.5.1 Legislation

The peaceful use of nuclear energy, safety of nuclear installations and radiological protection in Switzerland are governed by a legal and regulatory framework consisting of Federal constitutions and acts, ordinances and regulatory guidelines.

The Nuclear Energy Act (2003; "NEA03") was ratified to regulate the use of nuclear energy, and protect humans and the environment against risk. The act pertains to the regulation of nuclear goods, installations and radioactive waste, defined as "radioactive substances or contaminated materials no longer used" [310]. The act outlines nuclear safety principles, including protective and preventative measures required to comply with international standards at all stages of development, from design through to operation. It also places licensing obligations on operators of sites utilising nuclear energy, including the deep geological disposal of radioactive waste (Article 35). Under the NEA03, operators must minimise radioactive waste generation, and waste generated in Switzerland should be managed in Switzerland. The operator maintains responsibility for the safe management and disposal of waste, including waste retrievability up until closure (Article 37), with the safety inspectorate holding responsibility for the supervision

of nuclear safety and security.

The Radiological Protection Act (1991; "RPA91") and Ordinance (2017) provide the legal basis for operational radiation protection in Switzerland [311], [312]. The RPA sets out fundamental principles for nuclear safety, including the national responsibility for domestic radioactive waste management. The act states more specifically the criteria for materials considered waste, such as nuclide specific activity levels and dose limits and constraints, based on the recommendations of the ICRP.

The Federal Act on the Protection of the Environment (1983; "EPA83") governs environmental protection provisions in Switzerland [313]. Under EPA Chapter 3, the prospective licensee of any installation that could cause substantial pollution to environmental areas is required to submit an environmental impact assessment (EIA) and report, which will influence decisions related to the planning, construction or modification of a plant, including licensing decisions. The EPA83 includes provisions for the limitation of emissions, and will regulate all activities related to geological disposal prior to the involvement of radioactive substances, which are then regulated under NEA03 and RPA91.

The Swiss Federal Nuclear Safety Inspectorate Act (2007; "ENSIG") governs the regulatory activity of the Swiss Federal Nuclear Safety Inspectorate (ENSI) (see 6.3.5.3) [314].

6.3.5.2 Organisations Involved in Waste Management

The National Cooperative for the Disposal of Radioactive Waste (NAGRA) is the delivery body for geological disposal in Switzerland. Founded by Switzerland's waste producers and the Confederation, NAGRA are responsible for the preparation and implementation of disposal for all categories of radioactive waste.

The Swiss Federal Nuclear Safety Inspectorate (ENSI), are the regulatory authority for nuclear safety and security in Switzerland [314]. ENSI are responsible for the implementation of the legislative and regulatory framework for spent fuel and radioactive waste management, ensuring

operator compliance with radiation protection, nuclear safety and physical protection measures and reviewing of licence applications. They regulate on safety and security, whilst maintaining independence from licensing decisions under the NEA03.

The Federal Office of Energy (SFOE) solicit ENSI opinion when assessing safety analyses undertaken by the operator as part of licence applications. ENSI also assess the periodic safety reviews conducted by operators of NPPs, including waste management facilities.

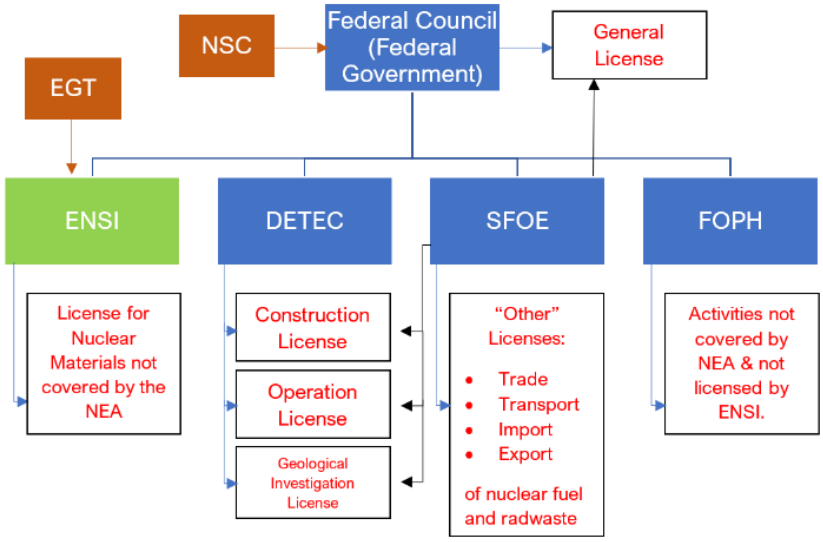


Figure 6.5: Authorities for licensing nuclear facilities in Switzerland.

A number of offices are responsible for administering licences to operators of nuclear installations in Switzerland. The Federal Council, informed by the Swiss Federal Nuclear Safety Commission (NSC), grant both the "General License" and "Closing Order" to operators. Four further licensing authorities exist within the Federal Government: the Federal Department of the Environment, Transport, Energy and Communications (DETEC), the SFOE, ENSI and the Federal Office of Public Health (FOPH), as in Figure 6.4.

6.3.5.3 Licensing and Permitting

The SFOE are responsible for the administration of nuclear licensing, and it is to them that prospective operators apply for the multiple licences and orders required throughout a facility's lifecycle. For a disposal facility, this will begin with an application for a licence to carry out geological investigations (GIs) to assess site suitability. The GI licence specifies the main aspects of investigations (location, extent of drilling, structures etc.), the investigations that require a permit and the scope of geological documents, and is granted by DETEC.

For all nuclear installations with consequential hazard potential, an operator intending to construct or operate a nuclear installation requires a General Licence under the NEA03, issued by the Federal Council. Operators are subject to a staged licensing programme (see Figure 6.5), commencing with the General Licence, detailing the licensee, site location and purpose, and for a disposal facility, criteria for site suitability and a site "protection zone". If an operator meets the criteria to hold a General Licence, they may submit an application along with an environmental impact assessment (EIA) and safety analysis report to the SFOE.

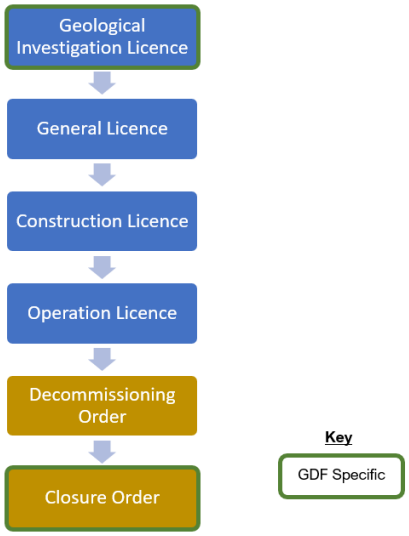


Figure 6.6: Overview of the licensing requirements for a Swiss disposal facility.

The environmental impact report must detail the existing condition of the environment at the site, proposed measures for environmental preservation, alternative solutions and any foreseeable environmental impacts. The Federal Office for the Environment review the EIA and ENSI the safety aspects of an operator's submissions. Meanwhile, the general licence application is made available for consultation. A review of the application and consultation responses is passed on to Federal Office and Cantonal government for consultation. The SFOE then submit their proposal to the Federal Council, who have the final say on the granting of the general licence.

The general licence does not provide the licensee permission to construct, which requires a construction license. Under NEA03 Articles 15-18, information regarding the submissions, criteria and contents of the construction licence application are set out, and includes factors such as installation capacity, technical implementation steps, preliminary emergency preparedness and all structures, systems and components. The process for obtaining a construction licence follows that of general licensing; DETEC are the competent authority responsible for granting a construction licence.

The application for an operation licence may occur concurrently with that for construction. Jurisdiction over the protection of people and the environment is now dictated by the RPA91. The submission of an updated safety analysis report, reviewed by ENSI, is required as part of the application process, along with the limits for releases of radioactive substances to the environment, measures for environmental surveillance and provisions to ensure the agreed safety, security and emergency preparedness requirements are met. Provided the operator meets the provisions of the previous two licences, fulfils the criteria set out under RPA91 for the protection of people and the environment, nuclear safety, security and emergency preparedness, an operation licence may be granted indefinitely by DETEC. The operation licence places the onus on the operator to ensure the safe operation of the facility. A special provision of the NEA03 requires a permit for the emplacement of each waste category in a disposal facility, administered by ENSI.

The licensing process ceases once a licence to operate a facility has expired under the NEA03, and has been surrendered by the operator. The operator is required to submit a decommissioning

project, including a timetable for decontamination, dismantling, demolition and management of radioactive waste to DETEC, in order to obtain a decommissioning order. The granting of a decommissioning order may occur once a facility is removed from operation, provided surveillance is maintained by the operator throughout the process of decommissioning. Once decommissioning has been completed, a closure order will be required for the disposal facility, granted by the Federal Council, subject to the review after a period of monitoring. The NEA03 requires the Federal Council to take steps to ensure information including location, design and inventory contained within the disposal facility is preserved, whilst the associated ordinance (Nuclear Energy Ordinance 2004) requires the host canton to enter information related to the protection area defined for the disposal facility in the land register [315]. The NEA03 also requires safe and permanent disposal should not rely on active surveillance or maintenance, though this may yet be stipulated, particularly relative to the protection zone established around the disposal facility. Decisions around institutional controls post-closure will be the responsibility of the Federal Government [310].

6.3.6 Regulating Geological Disposal in: Japan

Since 2000 the Japanese government have been engaged in a nationwide screening process to determine which municipalities contain sites that would be suitable for hosting a repository for the disposal of its high level waste. The siting process will be community led based on expressions of local interest. The 2011 Fukushima Daiichi accident led to an overhaul of the regulatory framework of nuclear installations in Japan; consistent with national policy, regulatory requirements for disposal by burial of higher activity waste are well established.

6.3.6.1 Legislation

In Japan, the Atomic Energy Basic Act ("Basic Act") is the overarching legislative tool for regulating the use of nuclear energy, enacted in 1955 as a means to securing future energy

sources and promoting academic and industrial advances [316]. Under the act, the use of nuclear energy is limited to peaceful purposes, and a party for the democratic implementation of nuclear energy policy required. The initial act sought to establish a Nuclear Safety Commission (NSC) to "plan, deliberate and determine" safety related issues with in the research, development and use of nuclear energy. Following the 2011 Fukushima Daiichi accident, the NSC was abolished, and an independent regulatory body established as per the amended Basic Act and Act for the Establishment of the Nuclear Regulation Authority ("NRA Act") [317]. The Nuclear Energy Preparedness Commission (NEPC) was also borne out of these amendments.

The Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors ("RRA57") was ratified in 1957 to apply regulatory oversight to all uses of nuclear energy in Japan [318]. It accounts for the regulation of activities throughout the nuclear fuel lifecycle including reprocessing, waste management and disposal, which are "Category 1" activities due to the concentration of radioactivity contained in the waste. The RRA57 sets out the role of the NRA, their relationship with the licensee and their authority over permissioning of activities through a programme of licensing.

The Act on Prevention of Radiation Hazards due to Radioisotopes, etc. ("RHPA"), regulates activities including waste management and disposal of radioisotope contaminated materials [319]. Under the RHPA, cabinet orders and NRA ordinances for enforcement of the act have been ratified, and provisions related to waste holder responsibility, and dose limits for exposure to ionising radiation set out. A special provision to the RHPA allows waste regulated under the RHPA to be treated as waste regulated under the RRA57, where disposal has been proposed and approved.

The Designated Radioactive Waste Final Disposal Act 2000 ("FDA00") sets out the framework for the implementation of geological disposal in Japan [320]. It established the Nuclear Waste Management Organisation (NUMO), under the supervision of the Ministry of Economy, Trade and Industry (METI). The FDA00 established a framework for the development of basic policy and a final disposal plan for high-level waste by METI, a repository site selection process and

provision for securing financial resources.

6.3.6.2 Organisations Involved in Waste Management

The Nuclear Waste Management Organisation of Japan (NUMO) is the Japanese delivery body for geological disposal. Their mission is "the Realization of Safe Geological Disposal of Radioactive Waste in Collaboration with the Local Community", giving priority to safety above all in a development that is sustainable and widely accepted by the public. NUMO is responsible for carrying out site selection and implementing the design, construction, operation and closure of Japan's disposal facility.

The Nuclear Regulation Authority (NRA) is the nuclear safety regulator in Japan. The formation of the NRA addressed the lack of regulatory independence which was cited as a potential contributing factor to the events of Fukushima Daiichi. The NRA is responsible for the development and supervision of nuclear safety regulations and safeguards, in accordance with the RRA57 and RHPA and compliance with the Nuclear Emergency Act [321]. The NRA has developed Ordinances which specify technical standards and regulatory requirements for compliance with relevant legislation, and are responsible for the administering of permissions for the use of nuclear materials and development of nuclear facilities in Japan.

6.3.6.3 Licensing and Permitting

The licensing process in Japan is analogous to that implemented in the UK. Prospective licensees are required to submit an application to the NRA, their details and those of the proposed site, the properties and quantities of the inventory for disposal, methods for disposal and a construction plan for the facility. This must also include an "operational safety program" which outlines an applicant's system for implementing high safety standards including, measures for implementing relevant laws and operational safety, surface contamination, dose and emission monitoring and periodic assessment of the facility. Provided an applicant meets the licensing

criteria, and their operational safety program has been approved by the NRA, a licence may be granted to construct according to the approved facility design. The criteria stipulates the operator must have sufficient technical ability and financial basis and that the location, structure and equipment of the facilities meet the standards set out in ordinance.

Once granted a licence, the licensee is subject to staged permissioning, They must seek the guidance and acceptance of the NRA on matters including changes to prospective plans, facility design and construction methods and compliance with the NRAs Ordinance. Additionally, having obtained the licence for design and construction, the licensee must not operate the facility until the NRA have inspected the site and are satisfied the construction meets the approved design and technical standards set out in the Ordinance. Finally, until the approval of the NRA has been sought and granted for the operational safety program, operation will not commence for any waste disposal activity. The NRA having further authority to halt activities if it finds the licensee in breach of the regulations set out in the RRA57. Licensees of Category 1 facilities are subject to periodic regulatory inspections (conducted by the NRA), to observe and ensure that pre-operation (RRA57 Article 51-8) and throughout the lifetime of the facility (RRA57 Article 51-10), the performance of the facility is maintained in line with the technical standards stipulated by the Ordinance (RRA57 Article 51-9-2).

The process for decommissioning is also governed by the NRA and guided by the Ordinance of the enforcement of the RRA57. This is defined in RRA57 Article 51-25 in which it states the licensee is responsible for the dismantling of facilities, elimination of contamination and disposal of contaminated materials, in accordance with an NRA approved decommissioning plan. The standards for the prevention of radioactive hazard after the closure of waste disposal site state that institutional controls should not be required following the the permanent closure of the repository, however the NRA Ordinance (based on the Act) does require that the licensee shall continue to monitor for the potential leakage of radioactive material and take the necessary measures to prevent inordinate levels of radionuclide leakage [320].

6.3.7 Regulating Geological Disposal in: USA

Existing US law designates Yucca Mountain as the location for the proposed deep geological repository for disposal of SNF and other HLW in the USA. Efforts have been made since 2008 to remove the site from consideration, something the Biden administration have stated they are committed to [322]. The regulatory framework for disposal is well established. The position of the current administration regards the use of the Yucca Mountain site is not yet clear, and should it be discontinued, a new siting process will be required for a US GDF.

6.3.7.1 Legislation

The Atomic Energy Act 1954 (AEA54) is the fundamental law governing civilian and military use of nuclear materials in the United States [323]. The Act is the primary legislative tool for the governance of the possession and use of radioactive material and those facilities which produce, or use said materials. The Energy Reorganization Act 1974, gave responsibility to the Nuclear Regulatory Commission (NRC) for the licensing of nuclear installations, including "facilities used primarily for the receipt and storage of high-level radioactive wastes", except for those on US Department of Energy (DOE) sites [324].

Under the AEA54, the Atomic Energy Commission (AEC) was responsible for the implementation of safety regulations on civilian nuclear materials. The Energy Reorganization Act of 1974 established the NRC as a regulator separate from nuclear weapons activities, on whom regulatory authority and licensing responsibilities under the AEA54 were placed.

The Nuclear Waste Policy Act 1982 (amended by Energy Policy Act 1992) requires Federal Government (DOE) to dispose of High-Level Waste and Spent Nuclear Fuel in a deep geological repository **1992Energy27761992Energy1992**, [325]. It authorises the Secretary of Energy to construct a repository, the Environmental Protection Agency (EPA) to establish public health and safety standards for the protection of the general environment from offsite releases of radioactive materials, and the Nuclear Regulatory Commission (NRC) to establish regulations

and a regime for licensing, outlined in Title 10 of the US Code of Federal Regulations (CFR) [326], [327]. The NRC's regulations relating to the disposal of high-level waste are found under Title 10 CFR Parts 60, 61, and 63.

The Energy Policy Act 1992 (EPA92) requires the environmental regulator to develop radiation protection standards protect the public and environment from exposure due to radioactive waste disposed of at Yucca Mountain, which is codified in Title 40 of the US CFR along with those for non-Yucca Mountain sites [328].

6.3.7.2 Organisations involved in Waste Management

The management of radioactive waste in the United States is governed by three principal authorities, the Nuclear Regulatory Commission, the US Department of Energy and the Environmental Protection Agency.

The Nuclear Regulatory Commission's (NRC) remit includes the protection of public health and safety and of the environment, and the promotion of common defence and security at facilities including those for the storage and disposal of nuclear materials and waste. The NRC has established a technical basis, formulated and implemented regulations and guidance for safe storage and long-term waste management including disposal. NRC is responsible for the granting of construction authorization and nuclear licences, and the inspection and enforcement of safety regulations on licensed sites, unless they confer power to "agreement states" or US territories to regulate specific activities [329].

The US Department Of Energy (DOE), founded under The Department of Energy Organization Act (1977), is a cabinet-level office primarily responsible for policy on energy and safety in the handling of nuclear materials, including programmes involving nuclear weapons and the disposal of radioactive waste [330]. The DOE is accountable for the regulation of its own programmes, including developing technologies for handling, treatment, storage, transport and disposal. The DOE is also responsible for implementing the disposal of commercial SNF and HLW, with

internal assurance whose jurisdiction includes monitoring compliance with NRC regulations under Title 10 of the CFR, including 10 CFR 820, 830 and 835 which relate to Procedural Rules for DOE Nuclear Activities, Nuclear Safety Management and Occupational Radiation Protection.

The Environmental Protection Agency (EPA) is the United States independent agency responsible for matters of environmental protection. The EPA's Office of Radiation and Indoor Air is authorised to establish environmental standards for radiation releases to the environment and limitation of emissions of hazardous pollutants to the atmosphere, including for the protection of the environment from radionuclides, under Title 40 of the CFR "Protection of the Environment". They also provide technical assistance to radiation protection agencies implementing surveillance and inspection.

6.3.7.3 Licensing and Permitting

The NRC Regulations Title 10, Code of Federal Regulations (CFR) ("10 CFR") specifies the binding requirements placed on persons and organisations receiving a licence from the NRC for the use of nuclear materials or operation of a nuclear facility. Specific to disposal are 10 CFR Parts 60, 61 and 63, which relate to the disposal high-level radioactive waste in a geological repository, licensing requirements for land disposal of radioactive waste, and disposal of high-level wastes at the proposed Yucca Mountain site.

10 CFR 60 sets out the licensing process for the disposal of high-level radioactive waste in a GDF, including irradiated reactor fuel, liquid wastes originating from solvent extraction systems and solid wasteforms resultant from solvent conversion. 10 CFR 60.3 outlines the DOEs obligations for obtaining authorisation and a licence at a geological repository site. Subpart B (10 CFR 60.15-60.52) outlines the procedure and requirements for each step of the development process from pre-construction through to the termination of the license, including:

1. Pre-application Review

2. Licence Application

3. Construction Authorisation

4. Licence Issuance

Before applying for a nuclear licence, the DOE must conduct site characterisation and produce a site characterisation plan which describes the area and quality assurance plans for data collection, recording and retention. This must be accompanied by information describing the proposed activities, extent of excavations and criteria for assessing the suitability of the site. A notice of the plan is published in the Federal Register by the NRC, who assess the plan prior to publishing its decision via a "notice of availability". This doesn't constitute any commitment or assurance for granting a licence (10 CFR 60.18).

The licence application procedure and requirements are specified in 10 CFR 60.21-60.24. The DOE are required to include information related to the repository location, schedules for each step of the disposal process, an environmental impact statement (EIS), and safety analysis report (SAR), which details the sites material inventory, proposed activities, analysis of performance requirements and proposed controls over releases. The DOE must also include plans for the physical protection of HLW and safeguards, a programme for the control of materials and a summary of site characterisation work.

The EIS sets out the projected impact of the construction, operation, monitoring and closure of the repository, potential long-term effects of disposal, and impacts of transport of the wasteforms and the impact of not proceeding with the project.

The licence application, EIS and SAR are filed and the DOE is required to serve updated versions to the Atomic Safety and Licensing Appeal Panel for consideration and to a public document room within the vicinity of the proposed repository area.

The NRC is empowered to grant "construction authorization", and attach conditions to protect environmental values, provided their review and consideration of the documents and public

comment, deem it satisfactory. If the repository area and design are suitable for hosting the specified quantities and types of radioactive waste, without “inimical” consequences for common security and defence or environment, construction authorization (therefore a licence to construct) is granted.

Once construction of the repository is essentially completed in compliance with the authorisation granted, a licence to "receive or possess source, special nuclear, or byproduct material at a geologic repository operations area" may be granted by the NRC. The licence entitles the DOE to receive and possess radioactive waste at the geological repository operations area, pursuant to licence conditions (10 CFR 60.42 “Licence Conditions”) set out by the NRC, and a licence specification set out under 10 CFR 60.43. These conditions may include restrictions on chemical and physical forms or radioisotopic content of waste, on waste permitted per unit volume of disposal space and restricted access controls.

NRC regulations assign responsibility for the decommissioning of any licensed or unlicensed facility to the licensee/responsible party, who must first produce a decommissioning plan for evaluation by the NRC. The decommissioning program uses a dose-based approach for regulating decommissioning activities, and it continues to provide oversight throughout the decommissioning phase though a series of inspections, interaction, financial reviews and reviewing of the decommissioning plan as it evolves, to ensure compliance with the plan and regulations [331]. Licence termination is subject to adherence to NRC’s dose limits for a decommissioned facility, as set out in 10 CFR Part 20, at which point the site may be released for restricted (provided residual radioactivity on the site is ALARA; 10 CFR 20.1403 AND 10 CFR 20.1404) or unrestricted use (10 CFR 20.1402).

There are not any disposal facility-specific institutional controls envisaged for the US disposal facility; the EPA maintain and national network of sampling locations across the 50 states called "RadNet" which periodically samples the air, rainfall, and/or drinking water for gross radioactivity levels or for specific radionuclides, which will continue to be enforced throughout the entire disposal facility lifecycle, including post-closure.

6.4 Analysis of the Commonalities of International Programmes

Analysis of the various national programmes outlined in Chapter 6 provides a valuable insight into the way GDF's are currently being regulated. Whilst each of the countries studied utilises differing legal systems to implement their regulatory framework, they will benefit the UK who are subject to the same international conventions and obligations. Some common features were identified throughout these programmes which will be applicable to the regulatory framework for a GDF in the UK, which include:

- safety of people and the environment;
- a system of licensing;
- regulatory independence;
- goal-setting approach to regulation;
- responsibility and liability;
- staged regulation;
- justification, optimisation and minimisation; and
- consultation with interested parties.

As analysis of the features that are common in the above reviewed countries are given in Table 6.1. Many of these features were made patently obvious through the information provided in legislation and individual national reports to the Joint Convention, particularly those which pertain to specific requirements of the convention. Others, such as a goal setting approach, are more subjective and will be dictated by national policy and the nature of licence conditions attached by the relevant regulators. As such even those not marked with a ✓might indeed be implementing/seeking to implement a goal-setting approach to licensing of their GDF/DGR;

this could form the basis of future research to draw more in-depth conclusions about common features on international regulation.

Table 6.1: Commonalities identified in the seven national disposal programmes.

	Independence	Safety	Licensing	Goal Setting	Staged Regulation	Licensee Liability	Public Consultation
Finland	✓	✓	✓	✓	✓	✓	✓
Sweden	✓	✓	✓	✓	✓	✓	✓
France	✓	✓	✓	✓	✓	✓	✓
Germany	✓	✓	✓	✓	✓	✓	
Switzerland	✓	✓	✓		✓	✓	✓
USA	✓	✓	✓	✓	✓	✓	✓
Japan	✓	✓	✓	✓	✓		

Safety of people and the environment

The overriding aim of the regulatory frameworks in each of the seven national programmes studied was to ensure the safety of the public and environment, both now and in the future [332].

Licensing

All of the countries studied will utilise a nuclear licensing regime for their deep geological repository. Table 6.2 provides a brief overview of the licensing regime in each of the countries studied.

Table 6.2: Licensing regimes in the countries reviewed throughout this chapter.

	Licensing Style	Granted by
Finland	Decision-in-principle followed by multiple licences (Construction, Operation, Decommissioning) for a fixed period (10-20 years typical).	Government
Sweden	Dual licensing (under the Act on Nuclear Activities and under the Environmental Code) with stepwise regulatory authorisation.	Land and Environmental Court & Government
France	Multiple authorisation decrees (Creation, Commissioning, Modifications and Final Shutdown).	Government
Germany	Licence with option for splitting into several phases ("partial licences") of licensing for long construction and/or commissioning timescales.	Government (Federal Office for the Safety of Nuclear Waste Management)
Switzerland	Multiple licences (Geological Investigations, General, Construction, Operation) and orders (Decommissioning, Closure).	Government (Federal Office of Energy; Federal Department of the Environment, Transport, Energy and Communications)
USA	Authorisation for construction followed by licensing.	Regulator (NRC)
Japan	Licensing, with staged permissioning.	Regulator (NRA)

In each case, the operator is unable to commence specified activities on the disposal site without the relevant permissions. In the majority of cases environmental protection, nuclear safety and radiological protection are all covered under a single permissioning regime. The point at which permissioning is required depends on the practices in each country. For example in Switzerland it is a requirement of the Nuclear Energy Act that geological investigations conducted as part of the site selection process need a licence. The UK places a similar requirement on a prospective operator through the environmental permitting process, to obtain an environmental permit

for intrusive site investigation activities (e.g. borehole investigations). More commonly the earliest point of licensing seems to be for the commencement of construction. Finland, Sweden, Germany, Switzerland, USA and France all incorporate environmental impact assessments] into their licensing regime, unlike in the UK where it forms part of the land-use planning process [333], [334].

Independent Regulation

In each of the seven programmes, the regulatory body for safety is independent of the parties with a vested interest in the development of a GDF, such as local authorities, federal government, the delivery body, and prospective operators.

Goal-setting approach to regulation

A goal-setting approach allows the licensee to be flexible in how it delivers the regulatory goals including those relating to radioactive waste disposal. It enables licensees to promote innovation and tailoring it's approach to the specific nature of the nuclear activity being conducted i.e. allowing it to apply a graded approach.

Some of the countries studied apply a goal setting approach to the regulation of GDFs. In Japan the NRA aims to ensure regulation of public and environmental protection by setting out regulatory requirements with underpinning specific safety goals that the licensee must attain. The same is true of the ASN's approach in France whereby the ASN set out objectives for nuclear safety and radiation protection. In the USA, the NRC set out a number of general and additional criteria within their Code of Federal Regulations (CFR) for aspects of design, waste packaging and performance, such as for protection against radiation exposures and retrievability of emplaced waste. Germany similarly set out general protection goals against which licensee progress and compliance is assessed.

Licensee liability

In all of the national programmes studied in Chapter 6, primary responsibility for safety lies with

the licensee/operator as would be expected from contracting parties to the Joint Convention. As such, and with some of the countries studied being a party to to the Paris-Brussels Convention, the majority take a similar approach to third party liability by placing obligations for sufficient resources on the licensee. In some instances, the obligation to hold sufficient financial resource ceases upon closure of the GDF, handed to a national waste fund thereafter. Japan are an exception in that liability (for spent fuel and nuclear fuel cycle wastes) lies with a national fund management organisation for disposal.

Staged Regulation

Staged regulation is used in some of the countries that were studied for example programmes in Finland, France, Switzerland and the USA require multiple applications for authorisation, permits or licensing, much like in the UK, whilst Germany retain the option of partial licensing within their legal framework and multiple licences are.

Justification, Optimisation and Minimisation

All the countries studied comply with the International Commission on Radiological Protection (ICRP) internationally agreed principles for protecting human health and the environment against ionising radiation for nuclear activities. These basic principles are the justification of practices, optimisation of radiation exposure and the minimisation of dose limits.

Public Consultation

A common thread throughout the regulatory frameworks of these national programmes was the requirement for public and stakeholder consultation. Requirement 36 of the IAEA's General Safety Requirements (GSR) Part 1 places responsibility on the regulator to ensure appropriate means are in place to inform interested parties and the public about possible radiation risks associated with regulated facilities and any processes or decisions made by the regulator. In many instances, this is enforced through obligations placed upon the applicant, to hold public hearings or consultations such as those held or proposed in Finland, Sweden, France, Switzerland and the US.

It is anticipated that the UK GDF will be regulated much like any other nuclear installation (NI) in the UK. The regulatory framework for nuclear safety, security, safeguards, environmental protection is well established, as outlined in Chapter 7, and should reflect many of the commonalities drawn from international programmes. The mapping of the existing framework allowed for further analysis to be conducted on its appropriateness, in application to the GDF, in Chapter 8.

Chapter 7

Regulation of Nuclear Installations in the United Kingdom

7.1 Introduction

The purpose of Chapter 7 is to provide an overview of the regulatory landscape relevant to nuclear installations in the UK at present. The regulatory framework, as applied to facilities such as nuclear power plants, reprocessing and storage facilities, must be understood before it can be applied, in part or whole, to a GDF, which poses its own unique regulatory challenges. As such, the landscape, with respect to relevant laws, regulations and the role of regulatory bodies, and how they're applied in practice via licensing, permitting and permissioning to UK installations is set out in this chapter. This is followed by an analysis of the current framework, set out in Chapter 8, in which the applicability and suitability of current arrangements with respect to geological disposal are addressed.

7.2 UK Nuclear Installations- Legal and Regulatory Framework

There are a number of UK laws that pertain to the use of atomic energy and the storage and disposal of radioactive wastes, which provide the basis for an overarching regulatory framework for nuclear safety, security, safeguards, environmental protection and land-use planning.

7.2.1 The Energy Act

The Energy Act 2013 (TEA13) is an act primarily concerned with the decarbonisation targets in the UK, within which it sets out provisions and purpose for the independent, statutory regulatory body for the regulation of the nuclear industry, the Office for Nuclear Regulation (ONR) [335]. The functions conferred upon the ONR are outlined in Part 3, Chapter 4 of TEA13 sets out the ONR's functions; the remit set out in Chapter 4 includes the powers to enforce relevant statutory provisions, more specifically the NIA65 and Nuclear Safeguards Act 2000 (NSA) and consult and enforce nuclear regulations regarding nuclear safety, security, safeguards and the transport of radioactive waste.

7.2.2 Nuclear Installations Act

The Nuclear Installations Act (1965) (NIA65) was introduced primarily to enforce three main principles: nuclear site licensing, control over processes for the enrichment of uranium and extraction of uranium/plutonium from irradiated materials and the provision of a legal regime for the third-party liability of licensees [12].

Within the NIA, it is specified that no person is able to utilise a site for the installation or operation of any nuclear reactor (other than any which are comprised within a means of land, water or air transport), or any other installation of a prescribed kind in the UK, without a

nuclear site licence (Section 1, (1)). Under the NIA, the appropriate national authority for administering the licensing process, the Office for Nuclear Regulation (ONR), is provided with the power to attach conditions to the nuclear site licence they deem necessary in the interest of safety. These may include provisions for ensuring an efficient system is maintained for detecting and recording ionising radiation, and conditions related to aspects of installation design, siting, construction, installation, operation, modification and maintenance. As shown in section 7.4, this is achieved via the implementation of a set of 36, largely goal-setting licence conditions.

Any site for disposing of nuclear fuel or bulk quantities of radioactive matter may be prescribed under (Part 3, section 1, subsection 1(b)) the NIA65 for licensing; the complete list of prescribed activities in accordance with the NIA65 are set out in the Nuclear Installations Regulations 1971 (NIR71). [336]. The definition of bulk quantity for disposal was consulted on in November 2020 [337]. UK Government Policy is that the ONR will be provided with the necessary legislative and regulatory provisions to enable it to licence a GDF under the NIA65.

7.2.3 Environmental Permitting Regulations

The Environmental Permitting (England and Wales) Regulations (2016) (EPR) are the primary legislative tool for the regulation of activities potentially harmful to the environment or human health in England and Wales [4]. The EPR regulate environmental protection for both radioactive and non-radioactive substance activities. Section 12(1) of the EPR states "a person must not, except under and to the extent authorised by an environmental permit- (a) operate a regulated facility." and the regulations include a list of facilities required to obtain an environmental permit (EP). Schedule 23 of the EPR pertains specifically to "radioactive substances activities", defined as any use of premises for the purpose of keeping or using radioactive material, accumulation and/or disposal of radioactive waste on said premises. The EPR also defines the permitting process, including applications, alterations, public participation and surrendering of a permit, and the conditions required to meet international directives, such as the Basic Safety Standards Directive, and national policy. Within Schedule 23, the Environment Agency (and Natural

Resources Wales (NRW)) are empowered to grant an environmental permit to an operator, which they do via a staged regulation regime.

7.2.4 Radioactive Substances Act

Prior to the EPR, the Radioactive Substances Act (1993) (RSA) set out the regulatory requirements for environmental protection in England the devolved administrations. The RSA are now only applied in Scotland and Northern Ireland, in relation to radioactive substances activities, setting out the powers of the relevant environmental authorities, including the authorisation of disposal activities and the registration of the use and accumulation of radioactive waste not on nuclear licensed sites (exemption of nuclear licensed sites is also set out within the RSA) [3].

7.2.5 Health and Safety at Work Act

The operators of UK nuclear facilities are subject to the Health and Safety at Work etc. Act (1974) (HSWA) [338]. This places a fundamental duty on employers to ensure so far as is reasonably practicable (SFAIRP), that the health, safety, and welfare of all employees, and of the public, is maintained throughout the time in which its activities are being undertaken. Under TEA13, the HSWA is enforced by ONR, where previously it would have been enforced by the Health and Safety Executive (HSE) until radioactive substances activities relevant to nuclear safety commenced on a nuclear licensed site).

7.2.6 Ionising Radiations Regulations 2017

The Ionising Radiations Regulations (2017) (IRR) are secondary legislation under the HSWA applied explicitly to the use of ionising radiation, which set out the requirements placed upon duty holders to ensure the safety of workers and the public as a result of the use of sources of ionising radiation [339]. Compliance with the IRRs is regulated by the ONR through its regime

of inspections and assessment of the licensee's arrangements against the requirements of the regulations. The ONR's fundamental Safety Assessment Principles (SAPs) will act as guidance for inspectors to make judgements on the adequacy of the licensee's optimisation of worker and public safety (presented in safety submissions) with respect to ionising radiation throughout the design, construction, commissioning, operation and decommissioning phases of the project.

Within the IRRs, the concept of minimising exposure so far as is reasonably practicable (SFAIRP) is introduced (much like under the HSWA where dutyholders are expected to demonstrate that risks to workers and the public are ALARP. The duties of the licensee according to the IRRs, include the optimisation of protection to provide as high a level of safety as is achievable, including the restriction of exposure by means of engineering controls, adherence to employee dose limits (for the whole body maximum exposure is 20 $mSv.yr^{-1}$), and performance of a suitable and sufficient radiation risk assessment.

7.2.7 The Radiation (Emergency Preparedness and Public Information) Regulations 2019 (REPPIR)

The legal framework for off-site preparedness and emergency arrangements are the Radiation (Emergency Preparedness and Public Information) Regulations (2019) (REPPIR) and apply to all nuclear licensed sites, and will therefore apply to a geological disposal facility [340]. REPPIR places an onus on local authorities, to work in conjunction with the emergency services and site operator to produce off-site plans, which are assessed by the ONR against the requirements set out in REPPIR.

7.2.8 The Nuclear Industries Security Regulations 2003

The Nuclear Industries Security Regulations 2003 (NISR) govern the regulation of security on nuclear licensed sites in the UK [341]. Enforced by ONR, the NISR place an obligation on

the licensee to produce an approved security plan and outlines the duties of the licensee to ensure the physical protection of nuclear material and sensitive nuclear information (SNI) on the regulated site. NISR also outlines a reporting regime for events that compromise the security of the premises or confidentiality of SNI, including unauthorised incursions onto the premises, incidents involving firearms, explosives or incendiary devices and damage to buildings and/or equipment.

7.2.9 Nuclear Safeguards Acts & Regulations

The UK, along with the other weapons states (USA, Russia, China, France) have entered into voluntary offer safeguards agreements (VOAs) with the International Atomic Energy Agency (IAEA), as described in 6.2. The VOA specifies the UK's acceptance of IAEA safeguards subject to exclusions related to national security, despite the fact that as a named weapons state, they're not required to accept safeguards. As well as the VOA, the UK agreed, upon the signing of Additional Protocols in 1998 and 2018, to provide the IAEA with further information relevant to safeguards issues on specified sites [277]. The UK's safeguards arrangements are enforced via the Nuclear Safeguards Act 2000 (NSA00), Nuclear Safeguards Act 2018 (NSA18) and Nuclear Safeguards (EU Exit) Regulations 2019 (NSR19) [276], [342], [343]. These stipulate how information may be retrieved and conferred as part of the obligations of the Additional Protocol, such as the implementation of materials accountancy and control measures, and provides ONR as regulator of safeguards in the UK, with the power to serve notice upon any person for any information if they have reasonable cause to believe it is information relevant to the terms of the Additional Protocol [276]. The NSA18 was enacted to provide legal provision for the continued use of nuclear safeguards post-UK withdrawal from the EU (and the European Atomic Energy Community) [342].

7.2.10 The Planning Act

Finally, the Planning Act 2008 (PA08) pertains to the land-use planning arrangements for developments including Nationally Significant Infrastructure Projects (NSIPs) [344]. The PA08 designates a geological disposal facility as an NSIP, providing its purpose is for the final disposal of radioactive waste at least 200 m below the surface and natural and engineered measures combine to inhibit radionuclide release to the surface (Section 30A (2)). The development consent process outlined in 7.5 would be applied to bore hole construction, excavations and the construction of the GDFs surface and underground facilities.

7.3 UK Regulatory Bodies

7.3.1 The Office for Nuclear Regulation

The Office for Nuclear Regulation (ONR) is the independent regulatory body for the nuclear industry in the UK, which was formed in 2011 by Government by merging multiple organisations including the Nuclear Installations Inspectorate, the Office for Civil Nuclear Security and the UK Safeguards Office and Department for Transport's Radioactive Materials Transport Team. Its remit stretches to the regulation of nuclear safety, security, industrial occupational health and safety, transport of radioactive materials and safeguards across a range of facilities including those on the UK's 37 nuclear licensed sites and those on unlicensed sites (e.g. organisations who handle classified or sensitive nuclear information). In the context of the GDF, nuclear safety relates to all activities relating to the design, construction, commissioning and operation of both the surface and the underground facilities which mitigate accidents or accident consequences, as considered in the safety case, to ensure sufficient protection of workers, the public and the environment from radiation hazards associated with the high activity inventory [32]. The principles and approach ONR takes in making enforcement decisions are in the ONR Enforcement Policy Statement. The enforcement powers afforded to ONR include the ability to [13]:

- grant a nuclear site licence;
- attach, vary or revoke conditions to a licence;
- reduce the area of the licensed site;
- consent to particular actions, arrangement and documents (requiring ONR consent for amendments);
- request and assess specific information from the licensee e.g. a safety case;
- issue specifications regarding document submission or the way in which actions are completed;
- issue agreements to proceed with an agreed course of action;
- instruct the licensee to shut down specific operations;
- issue the licensee with improvement and/or prohibition notices, and
- revoke a nuclear site licence.

Implementation of the GDF site selection process and decision making on this issue is not within the jurisdiction of the ONR, though ONR will consult with the delivery body for the UKs GDF, Nuclear Waste Services (NWS), throughout the siting process and will not grant a nuclear site licence to until a suitable safety case has been presented, development consent has been granted and an environmental permit is obtained under the EPR.

7.3.2 Environment Agencies

The Environment Agency (EA) is the body responsible for the regulation of the environmental aspects of a GDF in England, including radiological discharges to the air, surface and groundwaters, and the authorisation of the disposal of radioactive waste. Created under the Natural Resources Body for Wales (Establishment) Order 2012, Natural Resources Wales (NRW) is the environmental

regulator for Wales [345]. Formal regulatory oversight of the GDF site by the EA/NRW will commence with the permitting of intrusive geological investigations (i.e. borehole investigations) on a proposed site. Their remit includes pre-application advice and guidance, assessment of environmental permit and NSL applications, granting of environmental permits to site operators, reviewing safety submissions and implementing a programme of periodic inspections of permitted sites.

7.3.3 Health and Safety Executive

The Health and Safety Executive (HSE) is a non-departmental public body of the UK Government, responsible for the regulation of conventional industrial health and safety in Great Britain. Created under and responsible for the enforcement of the provisions of the HSWA (and associated regulations), it will be responsible for industrial health and safety during initial site investigation activities on the GDF site, prior to the issuing of a nuclear site licence by ONR. Once a nuclear site licence has been granted, ONR will be the responsible regulator for industrial health and safety on the nuclear licensed site.

7.4 Regulatory Processes for UK Nuclear Installations

The licensee of any proposed nuclear facility is responsible for the development of the facility at every stage from site selection through the design, construction, commissioning, operation, closure, and decommissioning. Nuclear Waste Services (formerly Radioactive Waste Management Ltd (RWM)) is the entity tasked with the implementation of geological disposal of higher activity waste in England and Wales, and is expected to become the nuclear site licensee and the environmental permit holder for the GDF.

7.4.1 Regulatory Approach

The UK's approach to nuclear regulation is primarily goal setting. The responsibility for safety on the licensed site belongs to the licensee, and the licensee has the freedom to decide how best to comply with the safety goals and regulatory requirements set out as part of the nuclear site licensing process. As illustrated by Figure 7.1, nuclear site licensing will be applied alongside the environmental permitting process.

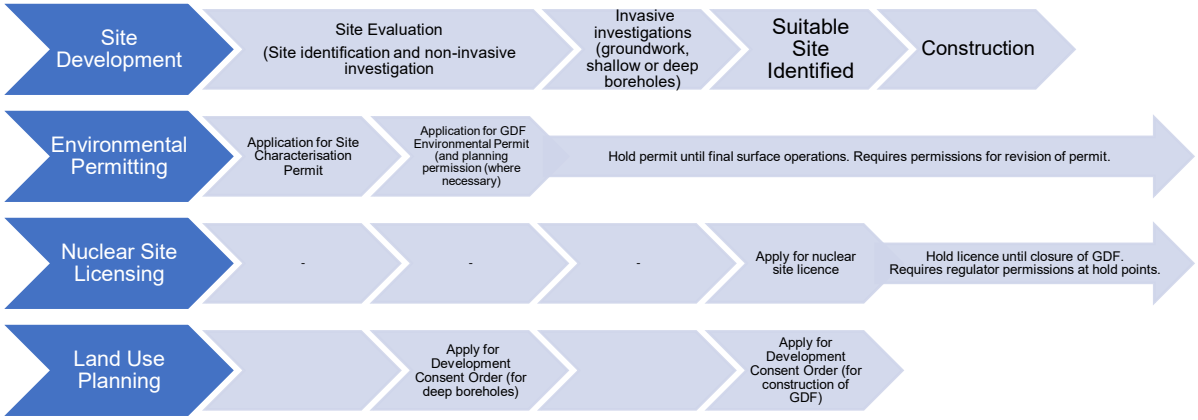


Figure 7.1: Overview of Geological Disposal Regulatory Process.

The GDF will be regulated in a staged or "step-wise" manner, dictated by the relevant permissions required by NWS under the relevant licence or permit conditions. As such the GDF lifecycle will be made up of a series of development stages and hold points, with NWS requiring ONR and/or EA/NRW permission in order to progress from one stage of the lifecycle to to the next.

7.4.2 Regulation of Nuclear Safety

In accordance with the NIA, any installation that is prescribed under the Nuclear Installations Regulations 1971 (NIR71) will require a nuclear site licence, administered by the ONR. [336]. A nuclear site licence contains site specific information, such as the address, location and the

nature of the permitted activities that are to be undertaken on the site. There are 36 standard licence conditions (LCs) that are attached to each nuclear site licence [346]. These conditions are designed to envelope all the activities that are needed to effectively manage nuclear safety on the site. The power to grant a nuclear site licence and the powers contained with these licence conditions allow ONR to control the design, construction, commissioning, operation, and decommissioning, of any installation on the site as outlined in Table 7.1.

Table 7.1: ONR's 36 Standard Nuclear Site Licence Condition

1. Interpretation	2. Marking of the site boundary	3. Control of property transactions	4. Restrictions on nuclear matter on site
5. Consignment of nuclear matter	6. Documents, records, authorities and certificates	7. Incidents on the site	8. Warning notices
9. Instructions to the persons on site	10. Training	11. Emergency arrangements	12. Duly authorised and other suitably qualified and experiences persons
13. Nuclear safety committee	14. Safety documentation	15. Periodic review	16. Site plans, designs and specifications
17. Management systems	18. Radiological protection	19. Construction or installation of new plant	20. Modification to design of plant under construction
21. Commissioning	22. Modification or experiment on existing plant	23. Operating rules	24. Operating instructions
25. Operational records	26. Control and supervision of operations	27. Safety mechanisms, devices and circuits	28. Examination, inspection, maintenance and testing
29. Duty to carry out tests, inspections and examinations	30. Periodic shutdown	31. Shutdown of specified operations	32. Accumulation of radioactive waste
33. Disposal of radioactive waste	34. Leakage and escape of radioactive material and radioactive waste	35. Decommissioning	36. Organisational Capacity

The licence conditions contain a number of primary (PP) and derived powers (DP). There are six primary powers, which are: specification, approval, consent, direction, agreement and notification, which enable the ONR to control the licensee's activities on the nuclear licensed site to provide assurance to the public and workers that nuclear safety is being managed appropriately.

Many of the LCs are goal setting and enable the licensee to "make and implement adequate arrangements" to meet the required regulatory goal. Some of these arrangements will provide the ONR with derived "powers". Similar to the primary powers, a derived power is an administrative level power granted to the regulator, particularly in relation to the control of activities using arrangements under arrangements in LC19-22 and 35-36. Unlike a PP, DPs are conferred voluntarily by the licensee, to allow ONR to apply proportionate oversight to specified activities. These powers will be dictated by the level of regulatory control required; a licensee may write into its arrangements any of the following derived powers: agreement, acknowledgement, specification or notification. The use of DPs within a licensee's arrangement has no statutory basis, and does not limit ONR or their ability to exercise the use of PPs stipulated in LCs [347]. ONR permissioning of activities in accordance with the DPs set out in a licensee's arrangements tends to manifest through the issuance of licence instruments (LIs), which come in multiple forms including an "Agreement", "Acknowledgement", "Specification" or "Notification" depending on the level of regulatory control required for the specific activity.

Where permissioning via the issuance of an LI is disproportionate to the hazard potential posed, enhanced implementation monitoring and control (EIM&C) may instead be utilised to permission activities. The licensee, through their own arrangements, can agree hold points with ONR for activities which are of less safety significance on the licensed site, and where the issuance of a LI by ONR is unnecessarily onerous. These hold points may be accepted by those with the delegated authority to issue DP LIs.

7.4.2.1 Nuclear Site Licensing Relative to a GDF

The nuclear site licensing process is made up of multiple steps of application, licensing and permissioning [13]. In order to apply for a nuclear site licence, the applicant must first ensure they are demonstrably capable of holding a licence. In preparation for this, they must establish themselves as a corporate body and develop the organisational and management capabilities required of a licensable organisation.

The NIA65 specifies only a corporate body can be granted a NSL (Section 3 (1)), which includes those registered under the Companies Act 2006, statutory corporations and Royal Charter bodies, and this body must be the user of the site. The ONR requires the licensee to be the "Controlling Mind" of all activities on the licensed site, to be able demonstrate sufficient knowledge of the plant design and safety cases (once developed) and act as an "Intelligent Customer" in the procurement of services and resources [348] and [349] (paragraph 66).

Having demonstrated they are a licensable organisation, the applicant next must develop a licence application dossier, which collates all application relevant documents. This should include a description of the licensable installations and activities, maps of the site and location and ownership details/leasing arrangements. The ONR also require as part of the dossier, a deliverable schedule of safety submissions which will lead to the formulation of a Pre-Construction Safety Report (PCSR), and a Safety Management Prospectus (SMP) which outlines many aspects of organisational capability including (but not limited to) the organisation structure, employment model, nuclear safety governance, emergency and licence condition compliance agreements and terms of reference for a nuclear safety committee. The applicant must also submit a site justification report (SJR) to the ONR alongside its application for a nuclear site licence, based on suitable and sufficient characterisation of the site.

The formal application process commences when the applicant makes a written application to the Chief Nuclear Inspector of the ONR and notifies the Secretary of State for the Department of Business, Energy and Industrial Strategy (BEIS). If the final GDF site is in Wales, it would

be the Welsh Government that would need to be notified of the application. Upon receipt of the application, ONR will make an initial assessment in order to estimate the timescale required to complete the assessment process. Typically, the assessment can amount to several years to allow time for cost recovery, the implementation of project management strategy and the preparation and completion of an assessment and inspection programme. Based upon the submission, the ONR project and site inspectors will develop an intervention strategy for assessing key elements of an application, which for the GDF will include assessment of the suitability of the site as measured against ONR siting Safety Assessment Principles (SAPs). This intervention will also assess the applicants proposed arrangements for compliance with LCs, the adequacy of the waste management and decommissioning strategy. In the case of a GDF the decommissioning strategy will need to take account of both the surface and underground facilities.

ONR will also assess the suitability of the security provisions, ensuring they are satisfied the applicant can manage all relevant aspects of site security during construction, operation and decommissioning; the regulation of security is summarised in section 7.5.

Following consultation with the relevant environment agency (REA), in accordance with NIA65 Section 3(13), the ONR will consider whether to exert the discretionary power granted upon them in NIA65 Section 3(4) instructing the applicant to notify public bodies of their application, including local authorities, emergency services and national park authorities. The prospective licensee for Nationally Significant Infrastructure Project (NSIPs), such as the GDF, is required to partake in consultations as part of the land-use planning process, under the Planning Act 2008, outlined in Section 7.7. Following public consultation, the ONR consults with BEIS who must justify, in accordance with the Justification of Practices Involving Ionising Radiations Regulations 2004, the benefits of disposing of radioactive waste in the GDF as outweighing the potential detriment to health.

The ONR will prepare a licensing report, which is reviewed by the Government Legal Department, and is used to inform the Chief Nuclear Inspector by making recommendations as to whether the GDF should be granted a nuclear site licence. The granting of the nuclear site licence

for the GDF would not automatically allow for construction with implications for nuclear safety, to commence. At this point, the prospective licensee and ONR will agree a regulatory schedule which identifies a series of hold points which allow ONR to exert regulatory control and permissions through its PPs/DPs.

It's probable that permissioning will be required on multiple occasions to reflect the modular construction of the GDF. The primary powers of "specification" and "consent" contained in LC19 (4) "Construction or installation of new plant" state where appropriate, the construction or installation should be divided into stages requiring the consent of the ONR to proceed between stages. In accordance with LC 19 (1), the ONR may also be granted derived powers to permission progress from one stage to the next. NWS will be expected to agree to a regulatory schedule with the ONR that identifies the appropriate hold points to be used in construction, commissioning and operation of the GDF, including the scheduling of the production and submission of all necessary safety documentation.

To support the start of the GDFs construction, it will be necessary for NWS as the licensee to provide ONR with a full site-specific Pre-Construction Safety Report (PCSR), which demonstrates that factors such as the geological conditions, proposed size of the site external hazards and proximity to local populations have been considered and are compatible with the proposed construction activities. The SJR submitted along with the site licence application should ensure that a site is suitable by this point in the development. Based upon the contents of the PCSR, ONR will use the PP afforded by LC19 (4) to specify the licensee is not able to commence nuclear safety-related construction without its permission. ONR may continue to exercise this power throughout the construction process to identify and implement suitable hold points, though as stated above, they may have already been granted DPs under LC19(1) to implement staged permissioning of the construction of the GDF.

During construction, the licensee will have agreed upon a regulatory schedule with ONR for the development of a Pre-Commissioning Safety Report (PCmSR), which must be submitted to ONR prior to the commencement of commissioning on the GDF site. The PCmSR should

demonstrate the safety of activities associated with the inactive and active commissioning of systems and components on the site meet regulatory requirements for nuclear safety. ONR and the licensee must also agree upon a schedule for the submission of safety documentation, building up to the formation of a Pre-Operational Safety Report (POSR). The ONR will, when satisfied, issue the relevant licence instrument to permit the commencement of commissioning. Again it is anticipated GDF commissioning will be staged, in accordance with the primary powers provided in LC21 (4) "Commissioning" or the derived powers inferred as part of LC21 (1). Once active commissioning period has come to a close, any learning or changes required to the PCmSR which have resulted from the inactive and active commissioning phases will be reflected in an updated PCmSR, which will feed into the formation of the POSR. The POSR will be assessed by ONR, and once they are satisfied that all issues arising from the POSR can be resolved by NWS, a LI for the commencement of routine operation can be granted. At the cessation of operations on the site the licensee will need to seek permission from the ONR to proceed with the decommissioning and clearance of the site. Due to the nature of the GDF's activities, it is anticipated that operation will cease at different times for the surface and underground facilities. Some areas of the surface facility may be decommissioned during the latter stages of the operational period of the underground facility such as surface storage facilities with no further use, whilst others such as surface access to the underground facility, will rely on the decommissioning and closure of the underground facilities before decommissioning and eventual closure.

The end of a licensee's period of responsibility for part or all of a nuclear licensed site will cease when the ONR give written notice that in its opinion there ceases to be any danger from ionising radiations on the site. The period of responsibility may also be brought to a close for part of a site, in the event of re-licensing, in which part of the previously defined boundary or installations contained within it are no longer contained in the terms of the new licence, or where the ONR grant a variation to exclude part of the site from the conditions of the licence. For a GDF, the requirement for the demonstration of "no danger" will mean different things on different parts of the GDF site. The surface facilities may all feasibly demonstrate no danger in

the same way as many other licensed nuclear installations; for the underground facilities, in which a large inventory of radioactive waste is to permanently reside, demonstration of "no danger" is much more difficult to quantify, and may need to be equated to something tangible such as the radiological risk at closure/during post-closure.

7.4.3 Nuclear Security Regulation Relative to a GDF

Nuclear security is regulated by ONR's Civil Nuclear Security and Safeguards (CNSS) division, and enforced in accordance with the provisions of The Energy Act 2013, relevant statutory provisions (outlined in TEA13 Section 82 "Enforcement of Relevant Statutory Provisions") and The Nuclear Industries Security Regulations 2003 (NISR) [341]. Within the legislation, nuclear security is divided into a number of parts: security at nuclear sites; security at other nuclear premises; security of the transport of nuclear material; and the security of sensitive nuclear information.

The licensee must provide ONR with a Nuclear Site Security Plan (NSSP), which systematically identifies the site and facility's categorisation with respect to theft or sabotage, identify vulnerabilities, which in the case of a GDF may be sensitive to the underground nature of activities, and provide supported arguments that the facility will be secure and in compliance with the requirements set out in the NISRs. NISR highlight that such a security plan must outline the standards, procedures and arrangements to be adopted by the licensee to ensure the security of nuclear premises, nuclear materials (category I, II and III), equipment used or stored in connection with activities involving nuclear materials and the security of sensitive nuclear information (SNI) kept on the premises (regulation 4(2)). The regulations do not stipulate specifically the arrangements an operator should outline in its NSSP, though the ONR's Security Assessment Principles (SyAPs) provide the foundation for the delivery of an effective security regime [350]. The fundamental security principles (FSyPs), which reflect UK law and international good practice outline many of the aspects required of a security regime, thus the NSSP and it's arrangements, including the requirements focused on:

Table 7.2: ONR's Fundamental Security Principles.

1 Leadership and Management for Security	2 Organisational Culture
3 Competence Management	4 Nuclear Supply Chain Management
5 Reliability, Resilience and Sustainability	6 Physical Protection Systems
7 Cyber Security and Information Assurance	8 Workforce Trustworthiness
9 Policing and Guarding	10 Emergency Preparedness and Response

Once the security plan has been approved by the relevant Secretary of State, the licensee is required to implement the plan and comply with its requirements. It is expected that an updated NSSP will be produced at each stage of the GDF lifecycle, to reflect the security risks associated with that part of the development and identify each of the aspects of operation and management which are important to achieving and maintaining security. For example, at the design stage, the NSSP and all it sets out will largely provide an outline of future conduct, and future iterations of the NSSP developing on the level of detail in areas such as implementing a graded approach to security risk identification, security personnel, assets and procedures and limits implemented in the interest of security.

The regulations also place the responsibility for the security of the transport of nuclear materials in the UK on the operator ("responsible person"). The licensee must submit a transport security statement (TSS) as part of their application which describes the standards, procedures and arrangements to be adopted by a carrier to ensure the security of the waste (and associated sensitive nuclear information (SNI)) consigned to the GDF site. Without a TSS (where waste is classed as category I/II nuclear material) and sufficient notice (no less than 7 days) to the Secretary of State, no nuclear materials may be transported to the GDF site.

7.4.4 Environmental Protection Regulation Relative to a GDF

The 2016 Environmental Permitting Regulations (EPR) apply to disposal activities including discharge into the atmosphere, seas, rivers, drains and groundwater and disposal to the land or by transfer to another site, and is not exclusive to radioactive materials. They are made up of 7 parts, enforced by the EA in England, and the NRW in Wales.

Schedule 23 of the EPR sets out Radioactive Substances Regulation (RSR)-specific requirements, repealing the RSA in England and Wales. It states that radioactive substances activities require an environmental permit "where a person uses premises for the purposes of an undertaking and...disposes of radioactive waste on or from those premises, " and "...receives radioactive waste for the purposes of disposing of that waste." including the GDF.

7.4.4.1 Environmental Permitting Relative to a GDF

Schedule 5 of the EPR outlines the requirements for environmental permit applications, including submission of applications, the duty of the regulator and scope for public consultation. In accordance with schedule 5 (1)(b), an application for an environmental permit must be made to the EA/NRW, by the operator ("applicant"). Applications involving proposals requiring substantial expenditure, such as the GDF, are encouraged once a detailed design and site plans have already been established.

Environmental permitting for the GDF will be implemented via a staged regulatory approach, as proposed in the EA's Guidance on Requirements for Authorisation for Geological Disposal Facilities (GRA) [259]. It will commence with the application for an environmental permit to conduct intrusive site investigations, such as borehole investigations, accompanied by an initial site evaluation (ISE), which sets out qualitative views on the feasibility of constructing the facility. If the application and ISE is accepted by the EA/NRW, the permit may be granted. Based on the outcome of intrusive investigations, the operator may then apply for a variation to the environmental permit, to ensure activities related to excavation and construction may

proceed under regulatory oversight.

In applying for an environmental permit for a radioactive substances activity, an applicant must submit forms provided by the regulator (EPR schedule 5 (2) (1)(a), (b)). All applications, nuclear or otherwise, require the applicant to complete and submit details of the individual(s), company, limited liability partnership or public or corporate body who are applying for the permit, and specify the location, site plan, and nuclear site licence status of the proposed site. This part of the application also requires the applicant to provide the EA/NRW with details of the local authority within which the site resides, sewerage undertaker (where appropriate) and whether the activity constitutes a justified practice under The Justification of Practices Involving Ionising Radiations Regulations 2004 (as amended in 2018).

A this stage it is likely that the relevant environment agency (REA) will request further information or submissions outlining the applicant and associated proposed activities, including a technical description of proposed activities, waste management arrangements and estimates of radioactive waste discharge, radiological assessments, operating techniques (including justification of Best Available Techniques (BAT) , discharge monitoring arrangements and details of any other permit applications, assessments or permits held by the applicant.

The requirements of the application process are tailored towards the purpose and scope of the facility/activity. For the GDF, this will include providing details of the origin, quantity and category of radioactive wastes consigned to the site, and details of the radioactive materials to be kept or used on the premises. The determination period for a permitting decision to be made commences once the application in full has been received by the EA/NRW; there is no statutory time limit for the determination of an application for a new permit on a NLS, allowing for coordination with ONR assessments. The timeframe for permitting decisions for the GDF will be influenced by the high level of public interest, as well as any further information requirements and the progress of the development consent order (DCO) application (see 7.3.5).

Applications for all radioactive substances activities, except those involving mobile radioactive

apparatus, are subject to public consultation in accordance with the requirements set out in EPR Schedule 5. This allows for public consultees likely to be affected by, or with an interest in the application, to provide "representations" to the EA/NRW for consideration in the decision-making process. The EA will furnish a response, including a final reasoned decision on the application to the applicant, and make it available to the public. Where the EA does not consider the applicant will act as the operator of the site, or believe that they will not comply with the conditions of a permit for the specified RSA, they are required to refuse an application.

Once a permit has been granted for the GDF, the EA/NRW are bound to periodic inspections of the environmental permits and the GDF under EPR 34 (1) and (2). They will also review an updated environmental safety case which reflects the operator's knowledge gained, and may implement a regime of independent monitoring, site inspections, audits and permit compliance.

A series of hold points will be established by the EA/NRW and permit holder, to integrate regulatory activities with updated environmental safety submissions, including a preliminary environmental safety evaluation (PESE), initial (IESC) and pre-operational environmental safety cases (POESC), discussed further in Chapters 8 and 9 [259]. At these points, an updated environmental permit will be granted to ensure the reflect the activities to be conducted in the next phase of the GDF's development e.g. receipt, storage and disposal of radioactive waste.

The EA act as consultee to ONR's de-licensing process, where NWS will need to demonstrate there is no significant risk to people or the environment in the removal of regulatory oversight. Due to the REA's involvement in de-licensing, NWS will not need to meet the two tests (set out in EPR Schedule 5, 14(1)) for the surrender of the environmental permit, after the period of post-closure monitoring has passed.

7.4.5 Land-Use Planning Regulation Relative to a GDF

Under the Planning Act 2008 (PA08), NSIPs require the granting of a development consent order (DCO), in conjunction with the relevant National Policy Statement (NPS). Under the PA,

the development of a radioactive waste geological disposal facilities, including the excavation of boreholes (at least 150 m in depth) and the construction of the GDF are NSIPs, and will be subject to the multi-step DCO process [344].

Prior to application for the DCO, the applicant is duty bound to consult any party prescribed under the PA, including statutory bodies, local authorities and the local community, on its proposed application for the GDF, as well as notifying the Secretary of State and publicising the proposed application.

At the pre-application stage, the applicant will also be required to generate and submit an Environmental Impact Assessment (EIA), including an Environmental Statement for the GDF under The Infrastructure Planning (Environmental Impact Assessment) Regulations or The Town and Country Planning (Environmental Impact Assessment) (Wales) Regulations 2017 [333], [334]. Applicants are encouraged to engage in pre-application discussions with regulators and relevant consultees at the earliest possible point to gauge their expectations on the nature, scope and contents of the Environmental Statement, and ensure any application takes account of all relevant environmental considerations. Where there are national security implications, such as the disposal of SNF, the NPS also recommends the applicant consult with relevant security experts to ensure all physical, procedural and personnel security and risk management measures have been adequately considered by the applicant.

The planning authority will consult the EA on the contents of the assessment, which should identify, describe and assess the potential direct and indirect effects of geological disposal on population and human healt, biodiversity, land, soil, water, air and climate and material assets, cultural heritage and the landscape.

Once consultation responses have been considered and the scope of the DCO application refined, an application can be made to the Planning Inspectorate (PINS). The application will demonstrate the suitability of the site for excavation of boreholes or the GDF, making reference to geological properties and the proposed inventory for disposal. Applicants are encouraged to

align their application for a DCO with their application to the ONR for a NSL.

The application is made public, and the examining authority assigned by the PINS given up to 6 months to examine the application under Chapter 2 or 3 of the PA, including a period of 3 months in which to consider the input of interested parties, before making its decisions and recommendation to the relevant Secretary of State. Within 28 days of receiving the application, a decision will be made by the relevant Secretary of State in consultation with the EA and ONR. At this point the applicant (NWS) will have 6 weeks in which to respond to the decision, and must publicise the outcome of the application.

7.4.6 Safeguards Regulation

Under the UK's VOA with the IAEA regarding nuclear safeguards, the regulator for safeguards in the UK, the ONR, submit nuclear material accounting reports and basic design information for all of the facilities offered to the IAEA under the agreement. The facilities and materials covered by the agreement are at the discretion of the UK.

Implemented under the Nuclear Safeguards Act 2000 ("NSA00"), the Nuclear Safeguards (Notifications) Regulations 2004 and The Nuclear Safeguards (EU Exit) Regulations 2019, the UK provide the IAEA with further information as part of an Additional Protocol as of 31st December 2020, extending to areas such as R&D, imports and exports. [276], [343], [351]. In the context of the GDF, the dutyholder is bound to report to ONR, any such information it has reasonable cause to believe constitutes "Additional Protocol Information" (API) under the NSA00. The ONR are also empowered to request information if it believes it to be API, which it does so via the serving of a notice to the dutyholder. Information is considered API if required by the ONR or Secretary of State in order to meet the UK's obligations under Article 2 of the Additional Protocol [277].

Under the Nuclear Safeguards (EU Exit) Regulations 2019 , further provisions are placed on licensees, requiring them to provide the ONR with technical characteristics of all qualifying

nuclear facilities, as stipulated in TEA. The GDF, storing and disposing of qualifying nuclear material, will therefore constitute a qualifying nuclear facility and NWS as the dutyholder, will be responsible for the provision of information to the ONR. It's expected this should include an annual programme of activities, including those related to the physical inventory on the GDF site [343]. The ONR may impose further safeguards provisions on the licensee, related to measures for determining the flow and stocks of nuclear materials, the frequency and procedures for taking physical inventories and arrangements for sample taking. The licensee is obligated to maintain a system of accountancy and control of nuclear materials, the contents of which should be made available for inspection by the ONR (EU Exit Regulations, Part 2, 6.). This should include an inventory change report, details related to the import and export of qualifying materials and provide special reports in the event of unusual occurrences or the loss/delay of materials during their transfer between sites.

Additionally, if international agreements specific to HAW apply in the future, under Part 13 of the EU Exit Regulations the licensee will be required to notify the Secretary of State for BEIS of the receipt, production, processing, derivation or fabrication of any HAW or its proposed transfer.

7.5 Implications for the Regulation of a GDF

Through the overview provided in Chapter 7, it is evident that many of the aspects required of a regulatory framework for a disposal facility can be found in the present framework applied to UK nuclear installations. There is a clear division of roles and regulatory responsibility over nuclear safety, security, environmental protection and safeguards issues in the UK regulatory framework, which has or is being successfully implemented to a plethora of different types of installation, with their own inherent risks and challenges. A geological disposal facility will be no different in this regard. However a GDF is unlike any other nuclear installation in a number of ways. The surface facilities for waste receipt and storage may appear as standard NIs, with

standard procedures and a type of facility which has been subjected to regulation already in the UK. However the deep, underground workings of a GDF are different any nuclear installation that has been regulated before. The regulatory requirements outlined in this chapter may not fully account for or address a number of GDF specific issues, including:

- the unique (for a nuclear installation) underground nature of the GDF;
- the large 3-dimensional (underground) footprint of the GDF, which extends laterally much further than the surface facilities' site boundary;
- the extremely long operating life, and length of regulatory control required;
- how the regulation of the GDF will be communicated to local communities, given the high public interest and length of GDF lifecycle.

The implications of each of these issues on the current nuclear regulatory arrangements will require significant consideration. It is possible that amendments to legal and regulatory instruments may be necessary to ensure the required level of regulatory control is exerted in the regulation of the GDF. An analysis of the existing UK regulatory requirements is provided in Chapter 8, conducted to identify how appropriate and proportionate they would be if implemented for the regulation of geological disposal.

Chapter 8

Analysis of Regulatory Requirements and their Effectiveness

8.1 Introduction

Chapter 7 outlined the existing flexible regulatory framework which has been utilised in the UK for the oversight of a range of nuclear installations. The UK policy stance on geological disposal is that it represents the most appropriate disposal route for the UK's inventory of HAWs, however the regulatory framework for the geological disposal of this radioactive waste has yet to be fully established. To understand whether GDF-specific issues can be accommodated in the existing framework, it was first important to map out the existing regulatory approach, as in Chapter 7. Additionally a number of national programmes, some of which are at a more advanced stage in the implementation of geological disposal than the UK, were investigated in Chapter 6. Chapter 8 builds on the findings of Chapters 6 and 7 to provide analysis on the appropriateness of the regulatory requirements in the UK, when applied to a GDF and their effectiveness. This was informed by aspects of regulation identified from the national framework, other national disposal programmes, the results of risk analysis conducted in Chapter 5, and stakeholder responses to a survey on the regulation of disposal.

8.2 Licensing Geological Disposal- Stakeholder Survey

8.2.1 Purpose and Scope of Survey

In the implementation of geological disposal, there will be a range of stakeholders who are interested or affected by the decisions made in the interest of nuclear safety, including waste producers, local authorities, interest local and national groups, the general public and the regulators. As such, it was appropriate to obtain a broad range of opinions on the composition of the existing regulatory framework for nuclear safety. The purpose of the survey was to obtain the thoughts of key stakeholders on aspects of the UK's regulatory framework for the geological disposal of radioactive waste, including what each stakeholder would like to see reflected in the regulatory framework, primarily centred on nuclear site licensing. The rationale behind this was to gauge the invaluable opinions of stakeholders affected or involved with the GDF project to broaden my own thinking and knowledge, looking forward to the production of the regulatory framework proposed in Chapter 9. It was not the intention to draw significant conclusions or data from participants responses.

The opinion of a number of stakeholders was sought- those consulted were:

- Radioactive Waste Management Ltd (RWM)
- Office for Nuclear Regulation (ONR)
- Environment Agency (EA)
- Low Level Waste Repository Ltd (LLWR)
- Électricité de France (EDF)
- Nuclear Legacy Advisory Forum (NuLeAF)
- Cumbria County Council (CCC)

8.2.2 Survey Findings

The stakeholders were presented with 13 questions, specific to aspects of the regulatory framework for safety, when applied to the GDF. These questions are contained in Table 8.1 along with a summary of the stakeholder's responses to each of the questions included in the survey, drawing together common themes or disparities in the responses. Responses to the survey were varied and to a degree reflective of the background and remit of the organisations or individuals participating.

Table 8.1: Summary of stakeholder survey question responses.

Question	Regulatory requirements / expectations
Question 1: Given the nature of the radioactive waste being disposed of and the role of a GDF, should the design, construction, commissioning, operation and closure of a GDF be regulated in the same way as any other nuclear installation?	Multiple stakeholders agreed that the current regulatory framework should be applied to the GDF, following the same procedures and rigour as other nuclear installations, including licensing, environmental permitting, development consent and third-party liability, considering the characteristics of the inventory for disposal. This aligns with current UK policy. Some caveats were provided, as it was highlighted that early stages of the development had the potential to compromise long-term safety, for which extra hold points, "staged regulation", would be necessary. Also highlighted was the significant timeframe of the GDF lifecycle requiring due care and attention to be given to the interface between regulatory regimes and the consent-led siting process.

Question 2: What are the significant or unique regulatory challenges posed by a GDF when compared to other nuclear installations that are subject to nuclear site licensing?	The regulatory challenges identified by stakeholders fell into three categories: public support/perception, underground activities and post-closure regulation. Both local interest and authority groups identified raising public awareness and encouraging public acceptance as a challenge more pertinent to the GDF than most other nuclear installations. It was also highlighted that effective regulatory interfaces (inter-regulator and regulator-public) need to be dealt with efficiently and transparently. Underground activities, their extent and potential for accidents, was raised as a significant challenge that must be addressed in a proportionate regulatory regime. Also identified was the challenging nature of removing regulatory oversight post-closure, given the inherent radioactivity that is in the GDF upon closure. The potential safeguards issues surrounding the disposal of safeguarded and non-safeguarded materials was also highlighted.

Question 3: Do you agree that the underground part of a GDF will require the licensed site to be defined in three dimensions in order to avoid unnecessary regulatory control at the surface level? If so, do you agree that the access connections from the surface part of the GDF to the underground galleries should be included in the definition of the licensed site?	The majority of stakeholders agreed that in some form the nuclear site licence should require a clear definition of the underground workings of the GDF to be set out as part of the licence dossier. Reasons cited included the lateral extent of activities/excavation, avoiding imposing regulation arbitrarily at the surface and ensuring the appropriate regulatory controls are applied only to the activities required. Interestingly a minority questioned the importance of defining this given the GDFs depth. It was pointed out that the EA utilise 2-D maps which could be just as useful if applied appropriately and are in discussion with RWM (now NWS) as to whether a 3-D description would be beneficial.
Question 4: Current nuclear site licenses require the licensee to post warning notices to delineate the boundary of the licensed site for the public, how should the boundaries of the of the underground part of a GDF communicated to the public?	Unanimously there was no appetite for physical delineation of the site boundary relative to the GDF's underground footprint. The example set by Hinkley Point C was raised as supporting evidence for how to manage this for the GDF.

Question 5: Should the underground and surface parts of the GDF be licensed separately or as a singular entity?	The appetite amongst stakeholders was that the surface and subterranean facilities should be licensed and permitted as a single entity. Provided a proportionate, risk-based approach is taken to the controls applied in specific areas of the site and an appropriate regime for the removal of regulatory control is implemented, none identified any requirements or basis for separate frameworks for regulation.

Question 6: Given that it will take hundreds of thousands of years for the radioactivity in a GDF to drop to the level associated with mined natural uranium, should regulatory control cease when the underground part of the GDF is sealed and the surface facility decommissioned and dismantled?	All stakeholders agreed that the requirement for licensing should cease once the GDF has been physically closed, as there should be no public risk requiring such stringent regulatory control. However it was pointed out that the mechanism for de-licensing is currently not a priority due to the large timescale to final closure and decommissioning. It was suggested that a phased approach to closure may be taken, which would require EA permissions in each case, effectively allowing for sealed vaults or tunnels to be deemed "closed", though what impact this would have on de-licensing requires further investigation. It is well understood that environment agency control will be maintained beyond the licensing regime and was highlighted that legislation relative to land-use planning (i.e. development consent for the future use(s) of the land), contaminated land (Environment Protection Act 1990 & The Radioactive Contaminated Land (Modification of Enactments)(England) Regulations 2006) and third-party liability (NIA) will still apply beyond the end of licensing.

Question 7: Should it be a regulatory requirement to communicate the location of a GDF post closure? If so, over what timescale and on whom should the responsibility fall?	Stakeholders suggested that in some form, information regarding the location of the GDF should be made available in the decades following the release of regulatory control, via records, public registers or archives. This is currently not mandatory, beyond the time specified in LC6. The example set by the low-level disposal site at Cherbourg, who introduced a process of record keeping with the countries Mayors was raised as a suitable type of arrangement, whilst other stakeholders suggested records should be passed onto the planning authorities post-closure. There is belief that maintaining records could help prevent human intrusion and should be fed into the regulatory framework.
Question 8: Are the current security regulations (Nuclear Industry Security Regulations) sufficient and appropriate to regulate security during the design, construction, commissioning, operation, and closure of a GDF?	Multiple stakeholders were of the opinion that the security requirements placed upon an operator should be sufficiently amenable, as moves are being made to take a more goal-setting approach (guided by the ONR's SyAPs), and that they should be fit for purpose in application to the GDF. It was acknowledged that many of the challenges relative to geological disposal are those which apply to other nuclear installations, including cyber security and data theft, physical security and worker access. The depth and multi-layered nature of the GDF led to many being confident the current regulations suffice for a GDF, and that post-closure regulation was unnecessary.

Question 9: Should a GDF regulatory framework relate only to the waste streams that are currently destined for disposal i.e. some LLW, ILW, and vitrified HLW, or should it include the potential for disposal of Spent Nuclear Fuel?	Though not yet "waste", SNF is declared in UK policy, as a constituent of the inventory for disposal. The position of the regulators is that the standards set out for an operator, which don't explicitly apply to the disposal of SNF and exotic materials, does not exclude them either, as such these requirements are flexible to changes if SNF is declared waste in the future. One stakeholder suggested that in theory SNF could be excluded from the nuclear site licensing framework if a decision has not been made at the time the framework is finalised. A common theme in responses was that the inherent risk attached to the disposal of SNF should require licensing and that the goal-setting regulatory framework should be applied proportionately if required in the future.
Question 10: Should the regulation of a GDF be based on prescription or goal setting?	The current approach to regulation is goal setting and given the novelty of a GDF programme, the majority of stakeholders agreed it would be appropriate for regulators to continue to govern in this way. The flexibility afforded to the licensee to meet the necessary safety and environmental protection standards is believed to enable proportionality in line with the hazards posed and the circumstances of the operator. Stakeholders believe this allows for further innovation and development of best practices which is amenable to the long GDF lifecycle, compared to a rigid, costly, prescriptive approach.

Question 11: There are clearly potential areas of overlap between nuclear licensing and environmental permitting, how can the regulatory regime for a GDF minimise these overlaps? Question 12: Where overlapping regulation cannot be avoided how can ONR and the environmental regulators, EA and NRW work together to provide effective and efficient regulation?	The majority of the stakeholders surveyed believed overlapping regulatory requirements and activities could be minimised through regular liaisons between the regulators, with clear lines of communication and roles established between the two. Both regulators suggested no such overlap existed and were confident that duplication of regulatory activities is minimised through their Memorandum of Understanding, driving effective communication between the regulators and establishing respective roles and responsibilities, and a coordinated regulatory system of activities and reporting. It was suggested that early correspondence with the licensee and between regulators and adherence to WENRA Safety Reference Levels on conflicting regulatory expectations should eradicate potential for conflict. It was also suggested that an integrated, single regulator for environmental protection, safety and security of nuclear installations would be appropriate and better suit the needs of waste producers.

Question 13: Does the reduction in the hazards posed by geological disposal (by minimising interim surface storage) render the current range of sanctions available to the environmental and safety and security regulators disproportionate/inappropriate?	The perspective of the regulators and delivery body is that the current framework is proportionate in its current state, with the necessity for minor tweaks tailored to GDF-specific challenges. It has also been highlighted however that local groups (planning authorities and communities) will play a vital role and that the framework needs to reflect their involvement. It is believed that justification should be provided as to why geological disposal is the correct route to take, compared to some management strategies which may be perceived as better for the local economy e.g. cycles of surface storage, as was suggested by the local authority contact who partook in the survey.

Issues or gaps in the regulatory framework identified from stakeholders responses are included in 8.3.3, 8.4.3, 8.5.2 and 8.6.2.

8.3 Analysis of Regulatory Requirements- Nuclear Safety

The ONR are responsible for the regulation nuclear safety on nuclear licensed sites, and as shown in Chapters 6 and 7 there are several requirements set out in international conventions and national legislation that shape the regulatory framework for nuclear safety that ONR enforce [12], [13], [262], [335], [336], [338]. The key legislation, international convention and international safety requirements are:

- Nuclear Installations Act 1965 (NIA65);
- The Nuclear Installations Regulations 1971 (NIR71);

- The Health and Safety at Work etc. Act 1974 (HSWA);
- The Energy Act 2013 (TEA13);
- Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (1997) (Joint Convention); and
- The IAEA Safety Standards.

The requirements of the Joint Convention are generally delivered by domestic legislation and regulations, at least in the context of currently prescribed nuclear installations. The applicability of UK legislation, for the regulation of geological disposal must be analysed if the regulatory framework is to aptly address the unique aspects and challenges presented by a GDF. No facility for the primary purpose of disposal has ever been regulated under nuclear site licensing, and some of the overarching legislation for licensing was conceived before UK policy dictated the GDF will require a licence. Once the framework has been reviewed and amended to meet the needs of the GDF, international obligations will have been met sufficiently according to Government [352].

8.3.1 Analysis of UK Nuclear Safety Legislation, Regulation and Guidance

Under the current framework set out by the NIA65 and the NIR71, the operator of a site intended for prescribed nuclear activities is required to hold a nuclear site licence. This is enforced by the ONR via a staged permissioning regime. More specifically the NIA65 requires that any person using a site for installing or operating a nuclear reactor or any other prescribed installation requires a NSL. Prescribed installations may include those for using or producing atomic energy, facilities for the storage, processing or disposal of nuclear fuels and bulk quantities of radioactive matter. Herein lies an issue with current legislation when applied to geological disposal.

Whilst the NIA65 does permit for the licensing of a facility for disposal, the NIR71 currently do not. Within the NIR, those "prescribed" facilities that may apply for a nuclear site licence (NSL) in accordance with the NIA65 are outlined in Regulation 3. In their existing form, the NIR doesn't include facilities for the disposal of any type of radioactive waste, meaning the NIA65 is only enforceable/applicable to GDFs surface facilities for the receipt and storage or HAW. It's accepted by both government and ONR that a GDF will require a NSL, and as demonstrated in 8.2.2, many expect that the surface and underground facilities should be regulated under a single NSL. As such, in order to enable a GDF to be licensed under the NIA65, it would be appropriate to amend nuclear safety legislation, for example by prescription of a GDF as an installation requiring a nuclear site licence under Section 3 of the NIR71. The issue of GDF "licensability" is addressed further in Chapter 9, Section 9.3.1.

8.3.2 Analysis of UK Nuclear Site Licensing

8.3.2.1 Suitability of Licence Conditions for the GDF

ONR has the power under the NIA65 to attach conditions to any nuclear licence "considered necessary or desirable in the interests of safety" and attach conditions that ONR "consider appropriate with respect to the handling, treatment and disposal of nuclear matter" [12]. The ONR's licence condition handbook sets out the 36 standard licence conditions (LCs) that are routinely attached to NSLs for existing UK nuclear installations. These combine a mixture of prescriptive and goal-setting licence conditions, which a licensee must comply with in order to meet the requirements of safety regulation and guidance.

In principle, each of these 36 conditions may be applied to a nuclear site licence for a GDF. The low relative hazard potential of a GDF might mean the level of regulatory oversight given to high hazard potential nuclear licensed sites is not proportionate. Given that the GDF is unlike any other installation licensed to date, consideration as to their applicability needs to be assessed. Analysis in Chapter 5 indicated that potentially exposed groups (PEGs) in the biosphere could

be susceptible to risks below the recommended guidance level (RGL) of $10^{-6}.yr^{-1}$ post-closure, and that the peak risks were not particularly sensitive to the design options or construction methods. However significant "engineering" is required in the design, manufacture, construction and installation of the engineered barriers to deliver these low risk levels. In view of this any changes to the current set of licence conditions is likely to be minimal. Throughout 8.3.2.1, each of the 36 LCs have been analysed for their applicability to geological disposal.

Licence Condition 1- Interpretation

LC1 sets outs the definitions and terminology utilised throughout the licence conditions and so for the most part requires no alteration in application to geological disposal [346]. It would be helpful to provide an interpretation of disposal specifically within the definitions set out.

Licence Condition 2- Marking of the site boundary

LC2 requires the licensee to make and implement arrangements to prevent the entry of unauthorised persons on the site, or parts of the site as ONR may specify, and to erect physical boundaries, such as fences or other appropriate measures, marking the boundary of the licensed site [346], [353]. For the GDF surface facility, LC2 can be applied in exactly the same way as at any other facility, however the underground workings provide a distinctly unique challenge, with much of the subterranean footprint extending beyond the physical surface site boundary. Hence the licensee's arrangements will need to show how the underground footprint is physically defined and communicated and how a record of the boundaries of the underground site will be maintained. It may be relevant to disapply the part of LC2 requiring demarcation of the boundary, for the underground facilities, with all entrances to the underground facility assumed to be contained within the surface site boundary, or adapt the language utilised in LC2 to encompass new, novel solutions to this issue.

Licence Condition 3- Control of Property Transaction

LC3 requires the licensee to maintain control over any transaction of property, of any part of the site, in order to ensure they hold overall control of the site [346], [354]. The arrangements made

by the licensee will reflect the hazard and safety significance posed by potential transactions involving each property on the licensed site, and for a GDF there's no reason to suggest it shouldn't be applied.

Licence Condition 4- Restrictions on nuclear matter on the site

LC4 requires the licensee to ensure that no nuclear matter is brought onto or stored on the site apart from that done so in accordance with adequate arrangements made by the licensee [346], [355]. LC4 is applicable to the GDF, for example as a means of controlling the first waste received on site, and to control the storage of radioactive waste prior to disposal. The requirements of LC4 will coincide with the licensee's requirements under the environmental permit regarding the acceptance of permitted materials on the licensed site.

Licence Condition 5- Consignment of Nuclear Matter

LC5 requires that the licensee shall not consign any nuclear matter or excepted waste to any site other than a relevant site without the consent of the ONR and requires records of any consignments of nuclear matter from the site to be recorded stringently [346], [356]. Whilst it is anticipated that only a small quantity of LLW or VLLW will accumulated on the GDF site, this might still need to be removed from the site in order to be disposed of appropriately on another site. As such LC5 would continue to enable the consignment of this to be controlled.

Licence Condition 6- Documents, records, authorities and certificates

LC6 requires the licensee to make adequate records that demonstrate compliance with any of the licence conditions, and adequate arrangements for the preservation of documentation for at least 30 years after the cessation of operations, though ONR's primary powers allow this term to be increased where deemed necessary [346], [357]. Given the active nature of the waste for disposal and the forecast length of the GDF lifecycle, application of LC6 is apt.

Licence Condition 7- Incidents on the site

LC7 requires the licensee to make arrangements to properly record, investigate and report

incidents on site [346], [358]. The reduced hazard potential of the GDF does not negate the possibility of safety-related incidents occurring on a GDF site, particularly underground, and so LC7 should still be applied proportionately to the GDF.

Licence Condition 8- Warning Notices

Under LC8, licensees are obliged to ensure sufficient and suitable notices are kept on site for the purpose of informing people on site of the meaning of warning signals, locations of emergency exits and actions to be taken in the event of a fire [346], [359]. Waste will arrive on the GDF site in a passively safe state, in theory reducing the risk of significant radiological events occurring. Nonetheless the inherent activity of the inventory and critically, given a large proportion of activities will be taking place underground, mean LC8 should still be applied proportionately to the GDF to ensure anybody present on site is aware of what actions are suitable in the event of a radiological or non-radiological emergency.

Licence Condition 9- Instructions to persons on the site

LC9 requires all persons entering the site to have received adequate instructions as to the hazards and risks associated with the plant and its operation, the precautions to be observed and actions required in the event of an accident or emergency [346], [360]. LC9 should apply to the GDF site given the nature of the waste inventory and the potential consequences of the mismanagement of an accident or emergency involving HAW.

Licence Condition 10- Training

Under LC10, the licensee must make and implement adequate arrangements for the suitable training of persons on site whose duties on any operation may affect safety [346], [361]. Safety-critical activities will take place across the GDF site thanks to the inventory and underground nature of activities, and so it is reasonable that LC10 be retained and enforced.

Licence Condition 11- Emergency arrangement

LC11 requires the licensee to make and implement adequate arrangements to deal with “any

accident or emergency arising on the site and their effects", including where necessary consultation with any person, local authority or body whose services may be required in order to fulfil these arrangements [346], [362]. The number of emergency or accident scenarios associated with geological disposal should be significantly reduced compared to higher hazard facilities, though not eliminated entirely, and hence LC11 will be applicable to a GDF. The primary powers provided to the ONR to approve licensee arrangements are apt, given ONR is also responsible for the oversight of REPPIR 2019 regulation compliance for offsite arrangements **UKParliament2019The2019b**, [340]. On-site plans will need to be coordinated with off-site arrangements for both surface and underground facilities on the GDF site, exemplified by the fallout of the radiological event which occurred at WIPP in 2014.

Licence Condition 12- Duly authorised and other suitably qualified and experienced persons

LC12 was written to ensure that only suitably qualified and experienced persons (SQEPs) could perform duties which may affect the safety of operations at a nuclear installation [346], [363]. Though the hazard potential for disposal is low, the nature of the inventory and safety-critical issues associated with activities on the GDF site mean the identification of suitably qualified persons to oversee or conduct them is sensible and proportionate.

Licence Condition 13- Nuclear Safety Committee

LC13 requires the licensee to establish a nuclear safety committee (NSC) for referral, consideration or advice on a number of areas including those implied through other LCs and arrangements, documents or safety matters as specified by the ONR [346], [364]. The LC requires that the NSC be made up people who hold sufficient qualifications, posts and relevant experience that any such matter may be advised on by the NSC. The NSC is part of the licensee's internal governance arrangements and hence is a vital part of the licensee's safety management arrangements, and would also provide public and political confidence in the licensee's ability to resolve matters relating to nuclear safety satisfactorily on the GDF site.

Licence Condition 14- Safety documentation

LC14 requires the licensee to make adequate arrangements for the production and assessment of safety case documentation at each stage of the geological disposal process from design through to decommissioning [346], [365]. The safety case is critical to the legal and social permissibility of the GDF, and hence as this licence condition requires the Licensee to have arrangements in place for the production and assessment of safety cases and safety documentation as required under other licence conditions relating to the design, construction, manufacture, commissioning, operation (including maintenance) and decommissioning, this is an important condition for a GDF licence and as such LC14 should be retained.

Licence Condition 15- Periodic Review

LC15 requires the licensee to make adequate arrangements for the periodic review and reassessment of their safety case documents and provides the ONR with primary powers for the approval of the licensee's arrangements and enables it to direct the licensee to conduct fresh reviews and assessments [346], [366]. This licence condition ensures the licensee will review the safety case for the installation periodically against existing safety standards and to look ahead over the next period to see if there are any life-limiting factors that could undermine the safety case. Given the expected operational lifetime of the GDF, carrying out periodic reviews will be essential and appropriate for the GDFs nuclear site licence. The low hazard of a GDF should enable the licensee to undertake its periodic reviews in a proportionate way with similarly proportionate regulatory oversight from ONR.

Licence Condition 16- Site plans, designs and specifications

LC16 requires the licensee to submit an adequate site plan and schedule detailing the particulars of each building and/or plant on the proposed site to the ONR, who are given the primary power to request further plans, designs or specifications they specify [346], [367]. No part of LC16 prevents the licensee's site plan from detailing both the surface and the underground areas of the licensed site. As such the lateral extent of the underground workings and scope for multiple levels of waste deposition within the repository can be easily accommodated for

under the terms of LC16. LC 16 is therefore appropriate for a GDF licence, and guidance on the specifics of the site plan will be provided by the ONR in discussion with the GDF licensee.

Licence Condition 17- Management systems

LC17s requires the licensee to have management systems that give "due priority to safety" such that any action or decision taken doesn't adversely affect safety, and requires quality management principles to be applied to all activities affecting safety [346], [368]. In order to adhere to international obligations (i.e. the Joint Convention) and given the safety-related issues and length of the foreseen operational period of the GDF, LC17 is suitable and necessary to ensure management systems are effective and driven by a strong safety culture. This condition therefore can clearly be applied to a GDF licence and should be retained.

Licence Condition 18- Radiological protection

LC18 was developed in response to Lord Layfield's suggestion for occupational annual dose equivalent measurements at Sizewell B [369]. It requires the licensee implement arrangements for the assessment of the average annual dose equivalent to specified persons on the licensed site, and to notify the ONR of instances where the limit, set by the ONR, is exceeded [346], [370]. The GDF inventory is highly radioactive, and the concurrence of construction and operation mean arrangements for the assessment of the dose equivalent to relevant personnel is appropriate.

The requirements of the Ionising Radiation Regulations (2017) to undertake radiation risk assessments and restrict radiation exposure will largely influence the licensee's arrangements to comply with LC18, and could challenge the necessity for the application of LC18 to the GDF given its reduced hazard potential, however this may contradict Lord Layfield's recommendations [339].

Licence Condition 19- Construction or Installation of New Plant

LC19 requires the licensee to make adequate arrangements to control the construction or installation of any new plant on the nuclear licensed site, in compliance with the design intent

and safety case throughout construction [346], [371]. Regulatory control of construction is essential, especially as in a GDF both construction and operation will take place in parallel for many years. As such LC19 is applicable to the GDF.

Licence Condition 20- Modification to Design of Plant Under Construction

LC20 places a requirement on the licensee to make and implement adequate arrangements to control design modifications which may impact upon safety [346], [372]. The length of the GDF lifecycle makes it feasible that changes to the design, which may have an impact on safety, could be foreseen as international experience grows and informs best practices. As such LC20 is applicable to a GDF.

Licence Condition 21- Commissioning

LC21 requires the licensee to ensure that adequate arrangements are made for the commissioning of a new plant or process which may affect safety [346], [373]. LC21 also stipulates that no plant or process which may affect safety is operated until the suitable stages of commissioning have been completed and reported on, and until a safety case which includes the safety implications of any modifications has been considered under the licensee's arrangements. The systems for waste handling, transport and emplacement are critical to maintaining safety on the GDF site, as such the oversight of commissioning provided by LC21 is justified.

Licence Condition 22- Modification or experiment on existing plant

LC22 requires the licensee to have provisions in place to control any modifications or experiments carried out to the existing plant or processes which may affect safety [346], [374]. Without adequate control over plant or process modifications, the safety of workers and the public can be put at risk, and as such it would be appropriate to attach LC20 to the nuclear site licence for the GDF.

Licence Condition 23- Operating Rules

LC23 requires that the licensee produces an adequate safety case to demonstrate the safe

operation of the facility. The operating safety case should “identify the conditions and limits necessary” to ensure safety is maintained throughout operation, these limits and conditions form the “operating rules” that operators must follow to ensure the plant remains within the safe working envelope [346], [375]. How a GDF is operated to ensure that radioactive waste containers are stored, handled and emplaced in a controlled manner will be important and hence LC23 is apt for the GDF.

Licence Condition 24- Operating Instructions

LC24 requires the licensee to ensure that all operations that may affect safety are carried out in accordance with written instructions. It also requires the licensee to ensure the plant operating rules are implemented through a set of operating instructions. [346], [376]. Given the importance of safety to the successful implementation and operation of a GDF, LC24 is again appropriate for a GDFs nuclear site licence.

Licence Condition 25- Operational records

LC25 requires a licensee to make provisions for the recording of the operation, inspection and maintenance of any plants related to safety, including the amount and location of radioactive material, including waste, used, processed, stored or accumulated on the site [346], [377]. LC25 is easily applicable to a GDFs surface facilities, but there are also underground plants and equipment important for the safe disposal of radioactive waste. It might be argued that until a gallery is closed the waste is in effect being stored (i.e. not disposed of) underground and hence having a record of what is placed and where it resides, is important operationally.These records would also be used to meet the requirements of environmental permitting once the gallery is closed and eventually when the GDF is finally closed. However the IAEA definition of disposal states "emplacement of spent fuel or radioactive waste in an appropriate facility without the intention of retrieval" defines disposal [378], as such the applicability of LC25 if the waste is indeed considered "disposed" of at the point of emplacement, could be questioned.

Licence Condition 26- Control and Supervision of Operations

LC26 requires the licensee to ensure that no operation which may affect safety can occur unless a suitably qualified and experienced person(s) is acting to control and supervise the operation [346], [379]. Given the activity levels of the inventory and the potential for accidents or incidents on the GDF site, particularly in the movement and emplacement of radioactive waste underground, LC26 is wholly applicable.

Licence Condition 27- Safety mechanisms, devices and circuit

LC27 requires that suitable and sufficient safety mechanisms, devices and circuits, properly connected and in working order, must be in place prior to any operations, inspection, maintenance or testing is allowed on a nuclear licensed site [346], [380]. A GDF requires numerous mechanisms or devices in order to ensure safety is maintained throughout the period of operation, for example in maintaining contact between surface and underground areas, thus LC27 is applicable.

Licence Condition 28- Examination, Inspection, Maintenance and Testing

LC28 requires the licensee to make and implement adequate arrangements for regular and systematic, examination, inspection, maintenance, and testing (EIMT) of any aspect of the plant that may affect safety, including provisions for the production of a plant maintenance schedule [346], [381]. Despite the low hazard potential, accidents due to plant malfunctions and failures could affect the availability of the GDF and this would have impacts on the operations and safety of other nuclear sites as well as having an adverse effect on public confidence. Hence LC28 remains relevant to the licensing of a GDF.

Licence Condition 29- Duty to carry out tests, inspection and examinations

LC29 requires the licensee to, when specified by the ONR, conduct "such tests, inspections and examinations in connection with any plant (in addition to any carried out under Condition 28 above)" that ONR see as necessary [346], [382]. This is an important reserve power for ONR and given the complexity of GDF and the implications of a major failure on the site, these reserve powers seem appropriate and LC29 applicable, to the GDF.

Licence Condition 30- Periodic Shutdown

LC30 requires a plant to be shut down in accordance with the plant maintenance schedule generated pursuant to LC28, if required for conducting EIMT activities [346], [383]. ONR has the power to specify if its consent is needed before the plant is restarted. The low hazard potential of handling, storing and disposing of passively safe, conditioned waste, enables the licensee to develop proportionate requirements relating to restart conditions, and allows ONR to adopt proportionate regulatory oversight. LC30 is appropriate for a GDF licence to enable ONR to effectively control safety critical plant, given there will be a number of systems requiring statutory inspection and maintenance, such as lifts, vehicles and systems involved in transporting waste from the surface facility to the repository galleries. What may be questioned is how and when the primary power provided to the ONR to permit re-commencement should be applied, whether it should be used for all periodic shutdowns or only those which are critical to issues of radiological safety.

Licence Condition 31- Shutdown of specified operations

LC31 enables the ONR to direct the licensee, within any specified period, to shut down any operation, and not allow for it to re-commence until ONR has given its consent [346]. This is an important power for ONR not only to maintain high levels of safety, but also to provide public and political confidence in the regulation of the GDF, which is particularly important given a GDF is a unique installation, for which the siting process relies highly on public participation.

Licence Condition 32- Accumulation of radioactive waste

Under LC32, the licensee must make and implement arrangements for the minimisation of the production and accumulation of radioactive waste on the licensed site at any time, and for the recording of said accumulation (in essence duplicating a requirement of LC25) [346], [384]. The production of radioactive waste at the GDF site, through for example, inspection and maintenance activities or waste handling and transport, should be minimal and restricted to lower level operational wastes. LC32 is however appropriate as it applies to waste stored on site,

which will constitute the majority of activities conducted at a GDF's surface facilities upon receipt of waste for disposal. The licensee would have the freedom to produce arrangements that are proportionate to the hazard and that would not require disproportionate ONR oversight. However, the reserve ONR powers contained in LC32 would provide public confidence.

Licence Condition 33- Disposal of radioactive waste

LC33 provides the ONR with the power to direct a licensee to dispose of radioactive waste. This could be on an existing nuclear licensed site or from a nuclear licensed site. However, it should be clear how applying to LC33 relates to the plans for operation of the GDF [346], [385]. The inclusion of LC33 would ensure the licensee does not unnecessarily accumulate radioactive waste at the GDFs surface facility, and provides the ONR an appropriate reserve power for a site whose nature is disposal over accumulation, hence this LC is appropriate for a GDF licence.

Licence Condition 34- Leakage and escape of radioactive material and radioactive waste

LC34 requires the licensee to ensure that at all times, radioactive materials, including radioactive waste, are controlled or contained such that it cannot leak or escape, that any leak that is reasonably practicably monitored, should be, and that it be recorded in accordance with the requirements of LC7 [346], [386]. LC34 places a clear legal duty on the licensee to put in place arrangements to prevent, monitor and control leaks of radioactive materials. This is particularly important given that there are likely to be long periods where construction and operation are happening in parallel, involving a large number of worked within a reasonable proximity of disposed waste packages. All waste consigned to the GDF will have had to meet stringent waste acceptance criteria (WAC), assessed by the ONR, prior to its receipt on site and hence the likelihood of any such leakage should be minimal. Though the possibility of damage in transit and the inherent nature of the waste disposed of in the GDF ensure LC34 remains relevant. The wording of LC34 does not discriminate between waste stored or accumulated on the site from that which has been disposed of, ensuring LC34 remains applicable to the GDF without amendment, and requirements would be applicable throughout the entire period of licensing.

LC34 is therefore relevant to a GDF and suitable for attaching to a GDF licence.

Licence Condition 35- Decommissioning

LC35 requires the licensee to make and implement arrangements for decommissioning, including the production of a decommissioning programme [346], [387]. It is important to be able show at the design stage that decommissioning has been considered so as to minimise the safety impact when decommissioning takes place. LC35 does not indicate when the decommissioning arrangements should be produced other than the arrangements should be in place before decommissioning commences. Hence it allows the licensee to take advantage of the length of the GDF lifecycle, over which significant technological advancement may occur (which could impact on decommissioning plans and proposals), before developing his decommissioning arrangements. LC35 therefore remains appropriate and easily applicable to the GDF.

Licence Condition 36- Organisational Capability

LC36 requires a licensee to make adequate arrangements to provide and maintain human and financial resources to ensure the safe operation of a licensed site [346], [388]. Given the length of the GDF lifecycle, it is vital that both of these resource streams are maintained. Maintenance of human resources will ensure the knowledge based built up in the early decades of the project is transferred, whilst maintaining financial resources will ensure the licensee sees the project through to completion. LC36 is vital to the regulation of a GDF.

8.3.3 Issues to be addressed in Nuclear Safety Regulation

8.3.3.1 UK Legislation and Regulation

As discussed previously, a key aspect specific to the disposal of HAW which is not currently addressed in nuclear safety regulation is:

- The "licensability" of disposal facilities relative to existing UK policy

  - Though policy requires a GDF to be licensed, the legislative basis for it being licensed is not fully established. This would require ministers to amend legislation, by prescribing a GDF or more broadly a disposal facility for highly active waste and/or spent nuclear fuel, as a facility which requires a nuclear site licence.

Based on the analysis of the licence conditions presented in 8.3.2.2, there are a number of areas which could be addressed in the regulatory framework to ensure it is proportionate and appropriate including:

- Defining disposal in the contents of the licence conditions
  - The GDF will be constructed to allow for the safe, permanent disposal of radioactive waste, and a definition of disposal would provide stakeholders with confidence in the ONR's ability to enforce and regulate disposal (given that under LC33 ONR are empowered to specify which waste is consigned for disposal), and confidence in the licensee to deliver against ONR expectations. It would also provide a clear distinction between operation and disposal at licensed disposal facilities, particularly where certain activities (e.g. waste emplacement) may be easily confused (i.e. waste emplaced is NOT considered to be disposed of until the definition of disposal is met). As alluded in the discussion under LC25, the definition of disposal provided by the IAEA might be used as a guide in making the distinction.
- Marking the site boundary and representing the underground footprint of the GDF
  - The GDF is unlike any other nuclear licensed site in the UK, due to the vast underground parts of the site. Disapplication or amendment of LC2(4) to accommodate for the vast nature of the underground parts of the GDF would alleviate issues of non-compliance on parts of the GDF site for which LC2(4) cannot be practically applied (this is discussed further in Section 8.3.3.2). This disapplication, accompanied by a 3-D representation of the site (as part of the licensee's arrangements under

LC16) which details coordinates (latitude, longitude and depth) would adequately address the underground site boundary issue. In light of any proposed amendments or disapplication of parts of LC2, it is important stakeholders can be confident that the extent of underground work is being considered and controlled appropriately, which a well communicated 3-D representation of the underground workings should provide.

8.3.3.2 Stakeholder Survey

Stakeholders were sought from a variety of backgrounds, and most in principle supported a nuclear licensing regime which functions as that currently implemented at other nuclear licensed sites; a single licence administered for the entire GDF site, with a goal-setting approach to regulation. However a number of further areas of focus were identified by stakeholders, which they believed would benefit the regulation of safety on the GDF site, including:

- the requirement for the safety regulator to have a higher level of regulatory focus on the activities associated with underground workings compared to the surface facility;
- the requirement for a clear, readily available 3-D representation of the underground workings of the nuclear licensed site;
- the need for the regulatory framework for the GDF to be flexible and accommodate policy decisions on the future disposal of other waste streams such as spent nuclear fuel (SNF) and exotic materials;
- disapplication of LC2(4) to the underground parts of the GDF;
- the potential of a single regulator for nuclear safety, security, safeguards and environmental protection on the GDF site;
- in the absence of a single regulator, clear and effective joint regulatory guidance

Regulatory oversight of Underground Activities

One stakeholder believed an increased level of "prescription", or regulatory oversight, would need to be placed on the construction, emplacement and closure of the GDF's underground facilities. This may be due to the unique, underground nature of the facility compared to the activities on other nuclear licensed sites, and indicated that more focus will be required in the oversight of underground activities compared to the surface facility, which present a relatively "standard" case by comparison. However, the stakeholder's concerns can be addressed without the use of a prescriptive approach as such an approach would reduce the flexibility afforded to the licensee to make and implement appropriate arrangements to control construction, operation and closure of the GDF. The application of the current nuclear site licensing regime allows for the regulator and the licensee to agree on what are appropriate arrangements to ensure safety is delivered. As a unique facility for the UK, this flexibility is critical in enabling the licensee to proportionately meet the challenges associated with implementing geological disposal. It is not unreasonable to assume that because of the unique nature of the GDF, additional regulatory guidance will be developed to assist the licensee in the development of its arrangements for construction and operation of the underground areas of the GDF .

3-D Representation of the Underground parts of the GDF

Many responses clearly identified a 3-dimensional representation of the site as something they felt was important to the regulatory framework to address, especially given the lateral extent of the underground footprint of the GDF compared to the surface site boundary. The issue is to ensure means are put in place to avoid unnecessary regulatory controls at the surface covering/residing above the underground footprint. Chapter 9 (Section 9.2.5.1) investigates how best this may be achieved within the definition of the licensed site, which as discussed above could incorporate the production of a 3D map of the underground facility.

Flexibility to Accommodate Future Policy Developments

As discussed above, one of the strengths of the current regulatory framework is the flexibility

afforded to the licensee to make and implement its own arrangements in the interest of maintaining high standards of safety. As pointed out by some respondents, the regulatory framework should also be able to accommodate changes in UK policy with regards to what is disposed of in the GDF. This is sensible as it is possible that in the future the Government could decide that SNF and exotic fuels, which are not currently defined as HAW, should be disposed of in the GDF. Under the NIA, the disposal of nuclear fuel is already covered and a licensed GDF would be able to accept the disposal of SNF subject to a safety case. Hence, the disposal of SNF at some time in the future would not require amendment to the current regulatory framework beyond those discussed in 8.3.1 and 9.2.1.1. One stakeholder did express concern about the disposal of plutonium, feeling it would compromise the safety case, design and cost of the GDF markedly, and would increase the level of safety, security and safeguards measures required. It would be astute for the regulators to ensure that the regulatory framework for the GDF will be able to accommodate the disposal of Pu if it is declared a waste in the future.

Disapplication of LC 2(4)

Some believed that it might be sensible and proportionate to disapply part (4) of Licence Condition 2 "Marking the site boundary" to circumvent issues surrounding the physical demarcation of the site boundary of underground facilities. A precedent has been set at Hinkley Point C, where access controls to the wider construction site, provided sufficient protection to those upon the site to allow LC2(4) to be disapplied on certain parts of the site. As argued above, stakeholders believed no tangible benefit would come from attempting to delineate the underground boundary, and that the sentiment of LC2 would be achieved through physically marking the surface site. Adopting the same approach as Hinkley Point C however comes with the problem that the GDF licence would apply to both surface and underground facilities and hence LC2(4) applies to both parts of the GDF. It is essential for legal reasons for the boundary of the site to be clearly established and this will be defined in the site plan attached to the NSL. The purpose of LC2 is to mark the boundaries of the site in which the legal requirements of the NIA65 apply. LC 2(4) gives the licensee the option to use "other

means" to achieve the purpose. Hence, for the underground parts of the GDF there will be a need for the licensee to develop a way to enable the 3-D boundary to be marked. It could be useful to add to the wording of LC2(4) to accommodate for these other means not physically "marking" the site boundary. This might be achieved by providing access to a 3-D digital render of the licensed site boundary displayed at all entrances to the underground part of the GDF. Land use planning controls around the site could also be used to prevent developments that would breach the underground site boundary.

A Single Regulator for Geological Disposal

The idea of a single regulator for the GDF was also pondered by one stakeholder. The proposal to have a single regulator to cover safety and environmental protection at nuclear licensed sites is not new, (with suggestions as early as the mid 1980s) but issues of practicality and politics have made this difficult to achieve. The merits and drawbacks of the application of this proposal to the GDF are discussed further in Section 8.7. The issuance of joint guidelines, to enable cohesive collaboration between the regulators, was also suggested; this is addressed through the Memorandum of Understanding (MoU) already in place between ONR and the REA, and should not require any amendment to the regulatory framework for application the GDF.

8.4 Analysis of Regulatory Requirements- Environmental Protection

Regulated by the relevant environment agency (REA), the primary requirements for environmental protection in England and Wales include:

- Environmental Permitting
  - Environmental Permitting (England and Wales) Regulations 2016 (EPR) [4]
  - Guidance on Requirements for Authorisation/Release [259], [389]

The permitting process is governed by the Environmental Permitting (England and Wales) Regulations 2016, which set out the responsibilities and powers of the EA for the administering of environmental permits. A proposed "staged" permitting programme allows for regulatory oversight over aspects of design, construction, operation and closure, as outlined in Chapter 7. In the UK there is already precedent for the permitting of radioactive waste disposal, and as such the regulatory framework for environmental protection is well established.

8.4.1 Analysis of UK Environmental Protection Legislation, Regulation and Guidance

The framework for environmental protection has been updated in recent times, such that its requirements better encompasses the regulation of disposal activities, including the disposal of radioactive waste. The EPR apply to waste operations (regulation 8(1)(c)) and include a schedule specific to radioactive substances activities (Schedule 23), including the disposal of radioactive waste. Therefore no obvious amendments are required in order for the regulations to be applicable to the regulation of the GDF.

Similarly much of the guidance which informs operators and regulators on how best to meet and assess regulatory compliance, in terms of environmental protection, disposal authorisation and release of regulatory control, have been developed with disposal in mind. The Guidance on Requirements for Authorisation (GRA) was developed for land-based disposal facilities that have or require authorisation under the Radioactive Substances Act (RSA) 1993. It sets out a framework within which the EA would regulate a disposal facility, and sets out the fundamental protection objective, and principles that REAs and operators should follow. However being developed in 2008, the GRA is no longer up to date with existing legislation, particularly the introduction of the EPR as the enforcement tool for permitting in England and Wales (superseding the RSA), as acknowledged in supplementary guidance. The Guidance on Requirements for Release from Radioactive Substances Regulation 2018 (GRR) was developed

in 2018 to be applied to facilities relinquishing regulatory control provides a marker with which the GRA will need to align [389].

8.4.2 Analysis of UK Environmental Permitting Regime

8.4.2.1 Suitability of Environmental Permit Conditions

The REA attach conditions to environmental permits to implement limits, regulatory oversight, and control over permitted activities. The conditions attached to permits for radioactive substances activities conducted on a nuclear licensed site are tailored to the particular activity, and at present over 50 standard conditions are proposed, which address:

- Management arrangements, competence and resources, "Management Conditions"
- Operating techniques, controlling operations on site, "Operating Conditions"
- Disposal of radioactive waste, "Disposal Conditions"
- Monitoring, measurements, tests, surveys, analyses, and calculations, "Monitoring Conditions" - Requirements for reporting/notification, "Information Conditions"

Conditions written for disposal activities have been applied to such sites as the Low-Level Waste Repository (LLWR); their applicability to a GDF is addressed herein.

Management Conditions

Conditions 1.1.1-1.1.5 relate to an operator's arrangements for implementing competent management of activities to which the permit applies across the site. This includes implementing management systems at the site (1.1.1) for which they can record and demonstrate compliance (1.1.2) and arrangements for waste management (waste management plan (WMP)) and environmental protection (site-wide environmental safety case (SWESC)), (1.1.3). They also require the operator makes a copy of the permit accessible to all those with duties relevant to the permit and that

they consult a suitable Radioactive Waste Adviser (RWA) on matters of environmental permit compliance (1.1.5). The requirements of 1.1.1 and 1.1.2 echo the sentiment of LC17 "Management Systems", LC36 "Organisational Capability" and LC6 "Documents, records, authorities and certificates", as such the application of these conditions to a licensed disposal site will require effective communication between regulators. The development of a WMP and SWESC are particularly relevant and important to the regulation of a GDF in demonstrating the radiological impact on people is ALARA whilst protecting the environment from the harmful effects of radioactivity. However, care should be taken in the management of regulatory expectations, given how the requirements of 1.1.3 for waste management and decommissioning planning mirror to an extent those of LC32 "Accumulation of radioactive waste", LC33 "Disposal of radioactive waste" and LC35 "Decommissioning". RWM (now NWS) readily consult with experts globally, and so it's fair to question whether the appointment of a specific RWA is necessary for the regulation of the GDF under 1.1.5.

Operations Conditions

The operating conditions in an environmental permit apply controls to which activities, operating techniques and materials are permitted on a site, and limiting factors including radionuclide limits and pre-operational actions or measures which must be completed before the specified operations can occur.

Condition 2.1.1 stipulates that the operator is only permitted to carry out activities on the site which are listed in Schedule 23 of the EPRs (specified in Schedule 1 of the permit) and 2.2.1 requires the operator to ensure that permitted activities occur within the boundary of the site as set out in Schedule 7 of the permit. Both of these conditions will be required for the GDF; 2.1.2-2.1.3 apply to sites utilising open sources and are not relevant.

Conditions 2.3.1-2.3.3 relate to the systems and equipment used to minimisation and monitor radioactive waste generated/released on the permitted site, and requires the operator to use the best available techniques (BAT) in its operating techniques. The principles of 2.3.3(a)-(b) can

be readily applied to the GDF, however 2.2.3 (c) should not be required, as it is not anticipated that radioactive waste for incineration will be generated on the GDF site.

Condition 2.3.4 requires the operator to maintain the systems and equipment utilised to meet the requirements of 2.3.1-2.3.3, to monitor and measurements that determine permit condition compliance or assess radiological exposure of the public and environment. The operator is required to ensure that these systems are in working and effective order at an "appropriate frequency" in accordance with 2.3.5 (which should be agreed upon with the REA), and that they shall comply with the criteria for the acceptance of these systems, equipment and procedures into service under 2.3.6. The requirements of these conditions, much like those set out under LC28 "Examination, inspection, maintenance and testing", are applicable to geological disposal. These conditions will be appropriate provided they are implemented proportionate to the low hazard potential associated with the anticipated generation of a small fraction of VLLW on the GDF site.

Condition 2.3.7 requires the operator to carry out activities in a manner that minuses the risk of pollution from non-radioactive substances in, or non-radiological properties of, radioactive waste. Ensuring operating techniques minimise non-radiological pollution is not a GDF-specific issue, nonetheless this is a condition that should be applied to its regulation in the same way that radiological hazards are considered, proportionate to their potential impact on the public and environment.

Conditions 2.4.1 and 2.4.2 require the operator to meet any information or improvement requirements, such as written plans or programmes of work to address waste production, by the date specified in Schedule 1 of the permit and to inform the REA upon completion. This allows the REA to impart regulatory oversight on specific issues and track operator progress over a set timescale, which is as suitable for permitting a GDF as any other nuclear installation.

Conditions 2.5.1-2.5.2 require that any pre-operational measures set out in Schedule 1 of the permit must be completed prior to the commencement of any of the activities set out in the

schedule. The exact nature of the REA's requests will be specific to the GDF and shan't be known until the programme has developed significantly, however these conditions provide the REA with control, via what is in effect a hold point, prior to the commencement of operations (relevant to activities that produce waste, discharge waste from the site or dispose of waste from the site). These conditions will ensure only activities and requirements proportionate to the hazard potential of the GDF are contained within the environmental permit for a GDF.

Conditions 2.6.1-2.6.2 relate to the operator's arrangements for the receipt of radioactive waste. The operator is required to produce a written specification of all the information they require of a waste consignor to enable the disposal of waste in compliance with permit or to sufficiently characterise not-currently-permitted waste to enable its future disposal (2.6.1). This provides the operator with sufficient powers to ensure that only waste suitable for disposal, with the relevant information, is consigned to the site and enables them to return waste which does not comply with the specification it sets out (2.6.2). Both conditions are suitable for application to geological disposal, particularly as only specific waste streams are specified in UK policy for disposal in the GDF.

Conditions 2.6.3 applies to operators of facilities receiving waste for final disposal on or from the premises. 2.6.3 requires the operator to inform the relevant local authorities of the origin, nature and timescales of waste consigned to the site. It makes sense to inform local authorities (and employ 2.6.3) as they'll be implicated in the GDF's emergency off-site planning, where knowledge of the radiological hazards on site will be necessary, and also be of local interest.

Disposal Conditions

Conditions 3.1.1-3.1.8 are specific to the disposal of radioactive waste on a permitted site. 3.1.1-3.1.3 state an operator must adhere to the limits, specific waste streams for disposal and the optimal disposal routes specified in Schedule 3 of the permit. This provides the relevant environment agency as the authority for disposal, an appropriate level of control over disposal and can be applied to a GDF without amendment. 3.1.4 allows the operator to dispose of waste

under the National Arrangements for Incidents Involving Radioactivity (NAIR) or RADSAFE Schemes, with the agreement of the REA. NWS do intend to become a member of RADSAFE, along all other UK nuclear site licensees, so 3.1.4 should be applied.

3.1.5-3.1.8 relate to the operator's arrangements for the transfer of radioactive waste off-site, including requirements to take direction from consignees (3.1.5), keep signed physical notes/records of consignments (3.1.6) and where necessary, waste is re-packaged and returned by the operator in accordance with transport regulations (3.1.7). It is anticipated that some quantity of LLW/VLLW, not to be disposed of in the GDF, will be generated on the GDF site, making 3.1.5-3.1.7 applicable. Condition 3.1.8 places a requirement on the operator to confer upon the REA records of all radioactive waste disposals. Given the nature of the waste for disposal and the main purpose of the GDF site, this condition is appropriate, but compliance should be managed in a way that aligns with the requirements of LC25 "Operational Records" and safeguards requirements for reporting, to ensure no undue burden is placed upon the operator.

Monitoring Conditions

The monitoring conditions (3.2.1-3.2.6) require the operator to implement and record a programme of monitoring activities, which is suitably accredited (i.e. via EA's Monitoring Certification Scheme), and whereby associated instruments are assessed and calibrated periodically. They also ensure the environmental regulator has permanent means of access to the permitted site and the power to require the operator conduct sampling, measurements etc. as specified by the regulator.

The inherent activity of the waste inventory means these conditions are largely applicable for permitting the GDF. Though the measurements and recording required to demonstrate permit condition compliance (3.2.1) echo somewhat the expectations set out in LC6 and LC22, and the operator's maintenance of records of all monitoring (3.2.2) is similar to the requirements of LC25 "Operational records". If monitoring activities impact on both nuclear and environmental safety, regulators need to ensure their expectations align without duplication of requirements . Equally,

the terms of 3.2.5 which allow the environmental regulator to specify any, tests, measurements analyses they require are similar to ONR's powers under LC29. The EA's powers under 3.2.5 may be disproportionate, as they will likely only be applied to the LLW/VLLW generated on site and so consideration should be given to the proportionate application of 3.2.5 and the frequency with which it may be applied, to the GDF. 3.2.6 requires operators to ensure that instruments utilised environment are checked and calibrated on a regular basis, much like the requirements of LC28 "Examination, inspection, maintenance and testing" (for systems affecting safety). Again, where regulatory expectations crossover, car must be given to ensure duplicate requirements are not placed on the operator.

Information Conditions

Information conditions relate to the records, reports and notifications required of the operator in accordance with the environmental permit.

4.1.1.-4.1.3 essentially set out criteria for record making to be legible, conducted as soon as reasonably practicable and retained until the REA specify, by the operator (4.1.1). Record keeping shall be essential given the length of the GDF lifecycle, and 4.1.1 should therefore be applied. 4.1.2 requires a copy of all records, plans and management systems to be kept on the site unless specified by the REA, and 4.1.3. requires the operator to retain and transfer records made in accordance with previous relevant permits issued to the operator. Transfer of knowledge and accountability are necessary to maintaining environmental protection across the GDF lifecycle, making 4.1.2 and 4.1.3 appropriate for a GDF.

4.2.1-4.2.2, allows the REA to specify the format, frequency and timescale of reporting and notifications in relation to radioactive waste disposal and activities undertaken. As EA are regulator authorising disposal, with jurisdiction over environmental protection, it is reasonable to assume these conditions should be applied to the GDF.

Conditions 4.3.1 and 4.3.2 cover operator notifications. Under 4.3.1, the operator must notify the REA following detection of malfunctions, breakdowns, failures, or accidents that have or

may cause significant pollution or radioactive waste generation, breach limits set out in the permit, lead to disposal routes not specified in the permit or other significant adverse effects. Though waste arrives passively safe and hazard potential is low, the inherent activity of the inventory makes 4.3.1 suitable for application to the GDF. 4.3.2 requires the operator to send any information specified in Schedule 5 of the permit when notifying in accordance with 4.3.1.

Conditions 4.3.5 and 4.3.6 relate to operators implementing changes which may impact on compliance with the permit. Under 4.3.5, any proposed changes made to management systems or resources that could impact upon permit compliance, must be communicated to the REA before implementation where possible. 4.3.6 applies the same principle to changes to documents including the WMP, SWESC, facility specific safety cases or waste acceptance criteria, which might be seen to impact upon the quantity or nature of radioactive waste disposal. REA can prevent the operator from implementing changes without their agreement. A large proportion of the UK's radioactive waste for disposal has already been conditioned, processed and packaged, as such changes to these submissions or systems could have implications on the design or disposal strategy initially authorised, meaning 4.3.5-4.3.6 remain applicable.

4.3.7-4.3.8 outline the procedures an operator must follow if the discharge from any of the outlets specified in this schedule exceed the Weekly Advisory (WAL) or Quarterly Notification Levels (QNL). Despite the passive nature of the waste and the low hazard potential, there seems little reason not to ensure the operator is adhering to WALs (4.3.7) and QNLs (4.3.8) given the active nature of the waste for disposal. Condition 4.3.9 relates to the loss or theft of open sources, and need not be included in a GDF's environmental permit on account of the lack of open sources on site.

8.4.3 Issues to be addressed in Environmental Protection Regulation

8.4.3.1 UK Legislation and Regulation

The generic permit conditions analysed in 8.4.2.1 were written specifically with disposal activities in mind, as such the scope or necessity for change or addition is minimal. However, specific to the permit for the GDF, it would be wise to consider if the language used in the condition which relates to the definition of the site boundary (Condition 2.2.1) accommodates for the extent of the underground facilities. A number of conditions attached to the permit for disposal at LLWR, the closest analogue to the GDF, don't appear in the generic conditions, which cover: [390]:

- Visual inspection of uncovered radioactive waste received on the permitted site
  - In principal, it should be the case that all waste consigned to the GDF has been meticulously checked in order to meet WAC and transported in line with transport regulations, such that all waste is transported in a robust and/or shielded form, such that no waste should be received by NWS on the GDF site in an uncovered state. Nonetheless, the inclusion of a permit condition, similar to condition 2.6.2 attached to the environmental permit for LLWR, would ensure NWS provides sufficient oversight in ensuring waste they receive is as expected, and as stipulated by the consignor.
- Compliance with waste acceptance activities prior to final disposal
  - The inclusion of a condition such as 3.1.8 in LLWR's environmental permit for disposal would ensure disposal of radioactive waste by burial, the primary objective of the GDF, is only permitted once all waste acceptance procedures have been completed by the dutyholder (NWS).

8.5 Analysis of Regulatory Requirements- Security

Security on a nuclear licensed site is regulated by ONR, through the Civil Nuclear Security and Safeguards (CNSS) division, who assess and approve licensee's security arrangements across the civil nuclear industry. The regulatory framework, expectations and activities are primarily shaped by:

- Nuclear Industries Security Regulations 2003 (NISR) [341]
  - Nuclear Industries Security Regulations 2003 Guidance [391]
- ONR Security Assessment Principles (SyAPs) and Technical Assessment Guides (TAGs) [350]
- Anti-terrorism, Crime and Security Act 2001 (ACSA) [392]

8.5.1 Analysis of Nuclear Security Legislation, Regulation and Guidance

The NISR place requirements on the licensee to provide the Secretary of State with a nuclear site security plan, updated throughout the installations lifecycle, and to have in place mechanisms for the reporting of incidents to the Secretary of State [341]. This also applies to the transport of categories I/II or III nuclear materials. The NISR has been applied prescriptively to comprehensively regulate the security of many UK nuclear installations, however the contents of formal security submissions are the responsibility of the dutyholder to make and justify. The requirements of the NISR are therefore able to be met proportionately by the licensee, which should allow NISR to be applied to a unique GDF site as with any other nuclear installation.

The NISR however apply to what are defined as "nuclear premises", in which nuclear or other radioactive material is used or stored, or other nuclear premises, premises other than on a nuclear site, where category I/II or III material is used or stored [341], [392]. The applicability of the NISR may therefore be questioned with regards to the GDF. As the GDF site will in part

exist as a nuclear premises utilised for storage, the regulations are ambiguous as to whether the NISRs apply to only the areas of the site used for storage, or the entire licensed site, including areas for disposal. Current guidance on security regulations does not provide clarity or make reference to disposal facilities and to what extent the regulations would be applied [391].

Also, "nuclear material" is defined in the NISR as in 77(7) of the 2001 Act, which refers to the definition given in Chapter 3 of Part 1 of the Energy Act 2004. which states it comprises "a) any fissile material in the form of- (i) uranium metal, alloy or chemical compound; or (ii) (plutonium metal, alloy or chemical compound;" or "b) any other fissile material prescribed by regulations made by the Secretary of State" [392], [393]. The NISR categorises nuclear materials, further subdividing materials into Category I/II or Category III. Currently HAW does not seem to meet the definition of "nuclear material", including the categories stipulated in the NISR, unless prescribed by the Secretary of State. However some HAW does contain quantities of nuclear materials, for which it is expected a classification will be determined. Should SNF, uranium or plutonium inventories be declared waste, they will be covered by the current definition. Therefore, clarity should be sought to identify where HAW is covered in relation to the definitions set out in the legislation.

As stated previously the licensee has "some" flexibility to make their own security arrangements, which it sets out in the site security plan, and which ONR advise should reflect its Security Assessment Principles (SyAPs) [350]. The site security plan will need to cover both surface and underground facilities; despite the security considerations for the surface and underground facilities differing, they are intrinsically linked and the security of the underground facility will be rely heavily upon the security of the surface facility. The SyAPs include 10 fundamental security principles (FSyPs) against which a nuclear installation is assessed. The principles reflect UK nuclear law and international good practice, and break down dutyholder activities into those which are strategic enablers, which create suitable conditions to support high reliability security arrangements, and secure operations which focus on the implementation and maintenance of nuclear security. These have laid the foundations for the successful regulation of security at

facilities across the UK, and there would be no significant issue in applying them to a GDF, provided amendments are made to the NISR which ensure all radioactive waste on the GDF site is covered by the regulations.

8.5.2 Issues to be addressed in Nuclear Security Regulation

8.5.2.1 UK Legislation and Regulation

The requirements of nuclear security legislation can be applied to a site for geological disposal as discussed in 8.5.1, but areas which could be addressed to ensure they better apply to the regulation of security on the GDF site include:

- The definition of "nuclear premises", inclusive of radioactive waste disposal facilities
  - Amendment to the regulations would allow for radioactive waste which has been disposed of to be regulated like waste which is currently considered "stored" on the nuclear licensed site, or differentiate between waste stored and disposed of on the nuclear licensed site, to ensure disposed waste is regulated up until the point of closure and de-licensing.
- The definition of "nuclear material", inclusive of higher activity radioactive waste
  - Prescription of HAW via the NISR would ensure all radioactive waste received at and disposed of on the GDF nuclear licensed site is covered by the NISR and security adequately regulated by ONR.

8.5.2.2 Stakeholder Survey

The stakeholders surveyed who had sufficient knowledge of the security requirements for nuclear installations indicated that the GDF posed largely the same security issues as other UK nuclear

installations, to which the relevant legislation and security assessments would still apply in their current format. Therefore no significant GDF-specific issues in the regulations were raised as issues relative to the application of nuclear security regulations to the GDF.

8.6 Analysis of Regulatory Requirements- Safeguards

8.6.1 Analysis of Nuclear Safeguards Legislation, Regulation and Guidance

The safeguards requirements for nuclear activities in the UK are implemented on a voluntary basis, (as discussed in Chapters 6 and 7) under domestic legislation which enforces international law. These requirements stem from the following:

- Treaty on the Non-Proliferation of Nuclear Weapons (NPT) [394]
  - Voluntary offer safeguards agreements (VOAs)
  - UK/IAEA: Protocol Additional to Agreement for Application of Safeguards in Connection Treaty on Non-Proliferation of Nuclear Weapons [MS No.12/2018] ("Additional Protocol") [277]
- Nuclear Safeguards Act 2000 [276]
- The Nuclear Safeguards (Notifications) Regulations 2004 (NSR) [351]
- Nuclear Safeguards Act 2018 (NSA18) [342]
- The Nuclear Safeguards (EU Exit) Regulations 2019 (NSR19) [343]

Licensee's nuclear safeguards obligations centre on material accountancy and ensuring that materials sensitive to proliferation are sufficiently inventoried and documented. The licensee for

the GDF will need to keep clear records which define how, where and when waste is received on the GDF site, plans for its storage (if required on the GDF site) and dates of final disposal such that regulators can be assured that there is no potential for the diversion of materials prior to disposal. Despite this, the IAEA expect and believe the applicability of safeguards to be terminated at the point of waste conditioning for most HAW, prior to shipment to the GDF site [395].

Safeguards requirements will need to be addressed however if the GDF is utilised for the disposal of SNF or nuclear materials such as plutonium or uranium, which would require the GDF licensee to implement safeguards reporting and monitoring arrangements. Once these materials arrive on the GDF site, they may be transported between multiple areas for inspection, handling or storage before final disposal, all of which present opportunities for the potential movement of materials away from their assigned location. It's therefore vital that in adhering to the requirements of safeguards legislation, this passage is sufficiently monitored, accounted for and reported. Credible diversion scenarios will be specific to the final design of the GDF, hence it is important to have an integrated approach to safety, security and safeguards in the design of the GDF. Diversion scenarios may include substitution of disposal containers, retrieval of SNF from the repository, removal of fuel assemblies or pins from disposal containers underground which is transported to the surface, and underground removal for processing underground [395].

The basic technical characteristics requirements set out under Part 2, 3.(2) of the Nuclear Safeguards (EU Exit) Regulations 2019, require the licensee to report upon the technical characteristics of the site [343]. These include factors such as design storage capacity and the layout of qualifying nuclear facility, demonstrating materials cannot be, are not and will not be diverted from the site without ONR consent. Much of the design information submitted under domestic safeguards legislation is shaped by IAEA consultation, which includes design information examination (pre-construction), verification (during construction), including inspection and monitoring activities to ensure undeclared activities, areas or equipment do not exist on the site, after which point "safeguards sealed" monitoring and accountancy will

be applied. The IAEA consider that with appropriate planning, application of routine IAEA safeguards poses no greater technological challenge than for any other nuclear installation, and that this approach should not inhibit the design process or compromise safety in application to the GDF [396].

8.6.2 Issues to be addressed in Nuclear Safeguards Regulation

The voluntary nature of the UK's safeguarding requirements and the IAEA stance on the requirements and their applicability to the GDF leave little scope for significant change or identification of gaps regarding their implementation.

8.6.2.1 Stakeholder Survey

Though the focus of the survey was largely on the regulation of nuclear safety, stakeholders highlighted nuclear safeguards issues relevant to geological disposal including:

- the management of safeguarded and non-safeguarded waste on the same site
  - The UK will require a novel administrative or operational approach to ensure both safeguarded and non-safeguarded materials can be accepted at the GDF without compromising the integrity of non-safeguarded materials (e.g. defence wastes) or increasing the risk posed by accepting both streams at the same facility. It will require parties consigning non-safeguarded waste (i.e. MOD) to work with IAEA to resolve
- long periods of concurrent construction and operation on the GDF site
  - The significant period of time over which GDF construction and operation occur may harbour potential opportunities for the diversion of safeguarded wastes on the GDF site.

It was posed that as a nuclear weapons state, the UK may be required to dispose of both safeguarded and non-safeguarded wastes. The additional protocol in place with the IAEA pursuant to the NPT, specifies which wastes in the context of UK nuclear activities constitute those which should be safeguarded. Non-safeguarded wastes, those which have been excluded from the scope of nuclear safeguards regulations (NSR19) for reasons of national security and/or defence, will have accountancy requirements imposed upon them by the Ministry of Defence (MoD). The licensee's arrangements to meet the MoD's requirements will need to be robust to ensure any safeguarding or security risks are protected against, and that it's congruent disposal with safeguarded waste does not significantly increase the safeguards risk posed. Safeguarded and non-safeguarded wastes should therefore be distinguishable to ensure the appropriate arrangements can be implemented relevant to each waste stream.

Another potential safeguards issue raised through this survey was the potential consequences of dual construction and operation of the GDF. Concern was raised surrounding the timescale over which this may occur, and the close proximity of excavation activities to disposal areas. The challenges this may pose might need to be rectified through novel approaches to safeguarding. However the application of the current UK safeguards requirements would suggest that diversion of wastes of interest are not particularly credible, as the wasteforms designated for disposal have been conditioned in a way which makes them difficult to separate for proliferation purposes. Should UK policy change, allowing SNF to be disposed of, it would be sensible to assess the current framework for safeguards to establish if and where changes should be made to UK safeguards requirements including more stringent oversight regarding the movement of safeguarded waste on the licensed site.

8.7 Regulatory Body Options

As demonstrated in Chapter 6, the involvement of multiple regulatory bodies in the oversight of a site for radioactive waste disposal is not uncommon. In the UK, as discussed in Chapter 7,

nuclear installations are regulated by the Office for Nuclear Regulation (ONR) and the relevant national environment agency (REA), either the Environment Agency (EA), Natural Resources Wales (NRW) or Scottish Environment Protection Agency (SEPA). Unlike some international disposal programmes, the ONR and REA both advise on and implement separate permissioning regimes.

Dual permissioning has been implemented in the regulation of many nuclear installations in the UK to date. There are multiple instances where the requirements of the environmental regulator mirror those of the ONR, as indicated in 8.4.2.1, which poses the question as to whether joint regulation is the best approach in the oversight of a GDF in the UK, or if an alternative solution, such as a single regulator approach, might prove more effective.

8.7.1 Joint Regulation

Joint regulation under the ONR and environment agencies has been a feature of the regulatory landscape in the UK since the formation of the nuclear safety regulator in 1960, including more recently the ONR in 2011. Though effective, it does present some challenges in ensuring duplicate or conflicting requirements are not placed upon the dutyholders of regulated facilities.

The application of separate regimes requires regulators to ensure any activities in areas of joint interest are coordinated, and are not likely to result in duplication of regulator and licensee activities. For example, the ONR regulate the safe conditioning and storage of radioactive waste on a licensed nuclear site, though the environmental impact of conditioning and storage is also of interest to the environmental regulators. In this example the regulators therefore need to work together to establish the requirements they place on the licensee, to ensure they are clear and that regulatory requirements relating to the safety of the treatment and storage of radioactive waste does not unnecessarily conflict with the requirements for disposal under environmental permitting legislation. Coordination of regulatory responsibilities and activities is important not only for effective regulation but also to avoid unnecessary work for the licensee.

Duplicate requirements should be avoided so that the licensee is not put in a position where compliance with one regulator's requirements sees the licensee in breach (or "conflict") of the other regulator's requirements. Establishing a "lead" regulator in each instance may itself prove a source for conflict which requires further resolution strategies and perhaps contributes to the case for a single regulator.

It may also be the case that expectations in areas of shared interest do not align. For example, suppose that aspects of the engineered barrier or repository design, expected to contribute to high safety standards, are detrimental to the post-closure performance of the repository and long-term environmental protection e.g. where rock supports are necessary to ensure safe operation, but have the potential to be detrimental to post-closure performance through interactions with other engineered barrier materials. In such an instance, this would require the licensee to carefully manage the expectations of both regulators by engaging in considerable consultation with them.

Feedback from both the EA and ONR as part of the stakeholder survey described in 8.2 suggested neither believe there is the potential for overlaps in regulatory jurisdiction or expectations when applying licensing and environmental permitting concurrently. They believe that through early, concerted consultation, and the prescription of enforcement powers in legislation, that each regulator has a clearly defined remit of regulatory responsibility, which is affirmed through a Memorandum of Understanding (MoU).

8.7.1.1 Memorandum of Understanding

The ONR have a Memorandum of Understanding (MoU) with the Environment Agency for matters of mutual interest in England, as well as with the agencies in Scotland and Wales, to ensure coordinated, conflict-free regulation of nuclear licensed sites [397]–[399].

Within the MoU, the areas that the ONR and REA are responsible for regulating are clearly defined. Whilst their regulatory purposes differ, the MoU acknowledges that communication,

consultation and joint working are required in order to sufficiently deliver a satisfactory level of oversight of regulated activities. It details the principles upon which working arrangements should be based, including a cooperative working relationship, structured interactions in strategy, planning, programming and operational regulation and where appropriate, joint work and engagement. This extends to ensuring the activities of one regulator do not inhibit the statutory responsibilities of another, and enforces consultation where a regulator intends to exercise its own regulatory power to issue, vary or revoke a permit or licence.

The MoU outlines ONR and REA's obligations for the disclosure of information, in line with the requirements of UK legislation, encouraging communication of information relevant to their counterpart, and the seeking of advice where necessary. Provisions for the resolution of disputes are also described; the ONR and REA are expected to firstly resolve disputes at a working level, escalating to directors in the event a resolution cannot be sought, and finally executive involvement should clarity still be required.

Efficient implementation of the MoU should be adequate in ensuring the effective joint regulation of the GDF site, and is an approach which encourages innovation and the maintenance of high standards in conducting regulatory activities. However, evidently the existence of two permissioning regimes necessitates a higher-level coordination and compromise, which might be avoided if a single regulator were to control all aspects of regulation on a licensed/permitted site.

8.7.2 Single Regulator

Some stakeholders indicated that they felt the best approach, which would avoid unnecessary conflict or a highly coordinated regulatory framework would be for both safety and environmental protection to be regulated by one body. This would require one organisation to absorb the relevant divisions of its counterpart involved in the regulation of nuclear installations i.e. the relevant environment agency to envelope the ONR or the ONR to take in the REA's nuclear

division, or for a new, single regulatory body encompassing safety, radiological environmental protection, security and safeguards to be established by law.

If the UK were to utilise a single regulator it would remove the requirement for a framework which coordinates multiple regulator's requirements and in principle, simplify the applications process for the licensee/operator. Areas of previously joint interest could be regulated more easily, as the regulator could work with the licensee to find the balance in the trade-off between environmental protection and nuclear safety rather than having to find agreement between three parties.

A single regulator model would enable an integrated approach to regulation to be developed, which requires the regulator to enforce the relevant safety and environmental protection legislations (i.e. NIA, EPR etc.) and would ease concerns over the early de-licensing of the nuclear licensed sited (compared to the point at which the environmental permit would be relinquished), given the regulator for nuclear safety would remain active on the site for many more years fulfilling duties related to environmental protection.

As outlined in Chapter 7, ONR regulate several facets of the activities conducted on nuclear installations in the UK and as such have a larger capability in the nuclear sector than the REA. Thus ONR would, in theory, be the more capable of the regulators in being able to absorb the capability of their counterpart. However the nature of the inventory for disposal in the GDF is such that regulation of environmental protection will be essential to the design, construction, operation and post-closure performance of the GDF, and any proposal to switch to a single regulator would require significant knowledge transfer/maintenance.

Whilst addressing some of the issues posed by joint regulation, without the need for an MoU, there are still multiple reasons why the regulators may choose to refute a single regulator approach. Firstly it would place all of the regulatory burden onto a single organisation, and for a significant period of time. Where currently the environmental permitting process would commence prior to intrusive site investigations, with the licensing process commencing prior

to construction, running simultaneously through to the post-closure monitoring of the GDF, a single regulator would have sole responsibility over what is a unique, significant infrastructure project for the UK, for 150 + years. This timeframe is not unprecedented, as sites like Sellafield and Dounreay will have been regulated by the ONR and it's predecessors for hundreds of year following the clean-up of their nuclear licensed sites. However a benefit of dual regulation over these timeframes, which would be lost by employing a single regulator, is how the presence of a second regulator can act as a driver for continuous improvement of standards and innovation in regulatory practices.

The feasibility of establishing a single regulator would require significant study and could throw up many issues or conflicts. Though ONR responsibilities are UK wide, disposal along with environmental protection is a devolved responsibility, and any change to this would require primary legislation in the face of strong political pressure from the devolved administrations, particularly those with no intention of hosting a geological disposal facility and/or which at present, have regulatory responsibility for LLW disposal activities. A single regulatory body would require UK-wide support and the absorbance of the radioactive waste divisions of the EA, SEPA and NRW for the sake of efficient regulation, the complexity of which may outweigh, at least in the short term, the benefits of a single regulator.

Based on the arguments provided throughout this section (8.7.2), there is not a compelling enough case for the integration of safety and environmental regulation and legislation, including the merging of those responsible for its enforcement, based solely on the requirements of implementing geological disposal. The time, resources and money required to implement such changes are better spent on improving the presence of nuclear energy in the UK's future energy mix, and aiding the implementation of geological disposal over the coming decades.

8.8 Summary of Challenges to be Addressed in Regulatory Framework for the GDF

The existing regulatory framework applied to nuclear installations would evidently accommodate, to a large extent, the regulation of a future GDF. In areas of nuclear safety and environmental protection, disposal is referenced in some of the regulatory requirements a licensee/operator must adhere to in order to comply with regulator expectations and national legislation. The current set of 36 standard licence conditions and generic environmental permit conditions largely apply to the regulation of a GDF in the UK in their existing forms. Nonetheless, there remain a number of areas that might need to be carefully managed or considered as the regulatory framework for a GDF is firmly established.

The regulatory framework will need to be comprehensive and transparent, and consider some challenges not previously addressed in the regulation of nuclear installations in the UK which are applicable, or specific to geological disposal including:

- marking and/or representation of the underground parts and site boundary in 3-dimensions,
- the demonstration of no danger and release from regulatory control
- the impact of the long lifecycle on regulatory oversight and licensee arrangements
- the potential for retrievability (dictated by Government policy),
- demonstrating compliance in underground workings.
- effective joint regulation
- proportionality of regulation given the reduced hazard potential
- security of the underground activities
- safeguards associated with the disposal of SNF and other nuclear materials

Having analysed the regulatory framework for nuclear installations throughout Chapter 8, for their applicability to the GDF, in Chapter 9 a regulatory framework is proposed which addresses the ambiguities or gaps identified as a result of the GDFs unique regulatory challenges.

Chapter 9

A Proposed Regulatory Framework for a Geological Disposal Facility

In Chapter 5, an indicative 1-D model was utilised to identify the impact of sensitivities in the key factors that influence the risk to people from a GDF, the aim being to see if particular activities in the design, construction and operation of a GDF would require more focused regulatory oversight. Chapters 6 and 7 set out the national and international regulatory landscapes for the regulation of nuclear installations and geological disposal. Chapter 8 analysed the applicability of the existing regulatory framework set out in Chapter 7, to the GDF. In Chapter 9, I address the GDF-specific issues, gaps in regulation and international best practices identified through Chapters 5-8, and propose a regulatory framework for the regulation of a GDF in the UK that is proportionate and consistent with international best practices.

9.1 Introduction

The UK's existing regulatory framework for nuclear safety, security, safeguard and environmental protection is enforced by nuclear safety and environmental protection regulators, i.e. the Office for Nuclear Regulation (ONR) and the relevant environment agency (Environment Agency,

Natural Resources Wales or Scottish Environment Protection Agency), as outlined in Figure 9.1. This framework is primarily driven by a goals-setting approach, which places much of the obligation around demonstration of safety and environmental protection (i.e. development of safety case, environmental safety case) on the delivery body/operator of a future GDF, and will be conducted in a staged manner (as touched upon in Section 7.4.1). The approach is somewhat unique in that it's less prescriptive than some of it's international counterparts, and also applies a staged approach to the granting of single licensing/permitting instruments (i.e. rather than new instruments being applied at the relevant stages of development, applications for amendment will be sought). Whilst it is apt that the majority of the regulatory framework for nuclear installations should apply to the regulation of the geological disposal facility (GDF), there are areas which, as identified in Chapter 8, would benefit from an update or amendment to sufficiently meet the requirements of the GDF. The purpose of this chapter is to propose how the GDF should be regulated, to ensure the safety of the public and the environment from the disposal of HAW in the GDF.

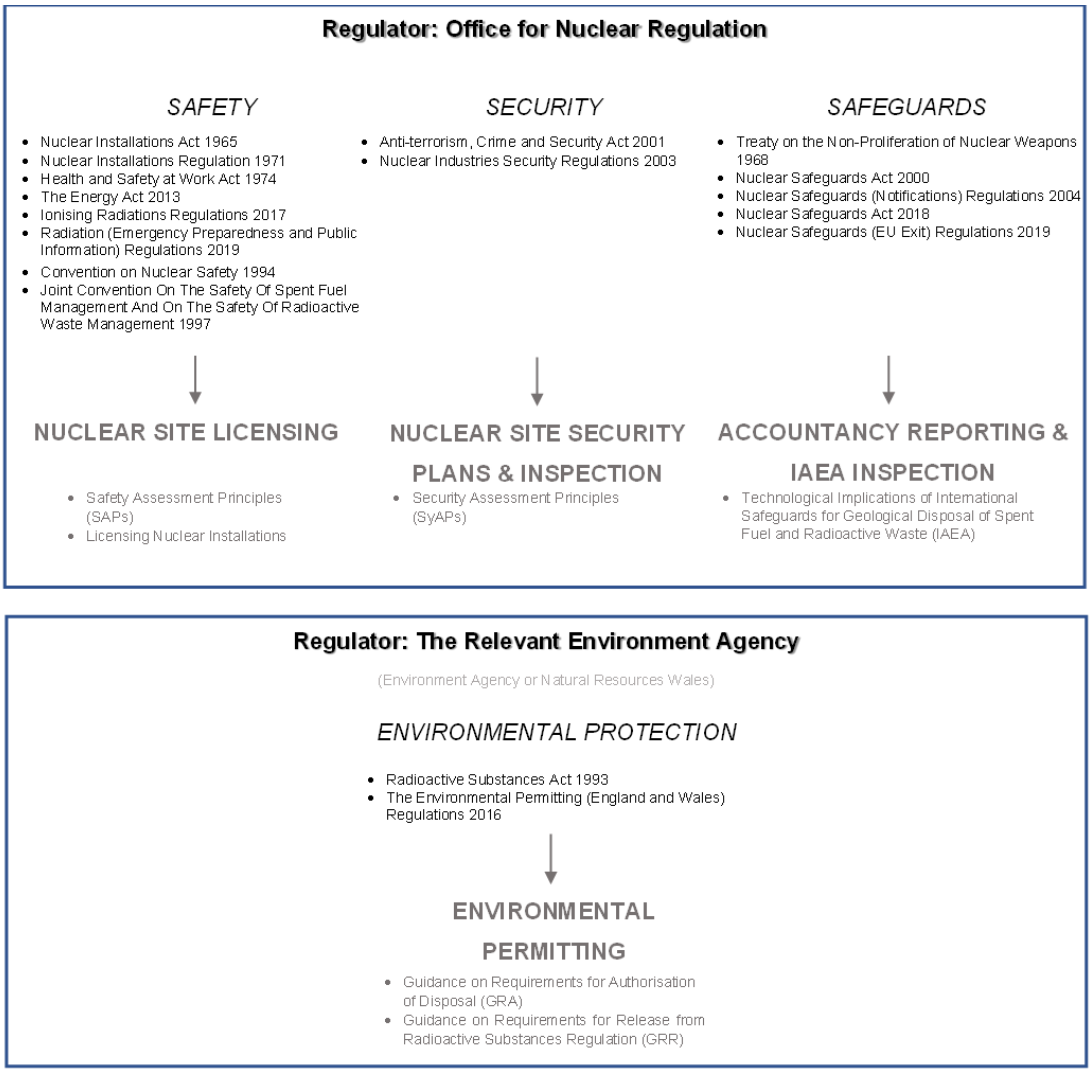


Figure 9.1: An Overview of the Regulatory Framework for Nuclear Installations in England and Wales.

9.2 Fundamental Regulatory Principles Applicable to the Licensing of a GDF

The mapping and analysis work conducted in Chapters 7 and 8, and UK policy on the regulation of the GDF, did not identify any scope for significant change to the application of the existing regulatory framework to the GDF, provided it is applied proportionately to the lower hazard potential it poses (vs. other NIs, such as NPPs). As alluded, the framework for the regulation

of environmental protection relative to the GDF is well established and caters much more explicitly for disposal than the framework for nuclear safety at this point. It's important to note that whilst the environmental regulators hold ultimate power over regulating disposal, neither regulator will be able to implement sufficient regulatory control over the GDF without the input and expertise of the other. As such, effective, proportionate regulation of nuclear safety, is appropriate and necessary to successfully implementing the wider regulatory framework for the GDF; to ensure this can happen a number of fundamental principles, borne out of the principles of nuclear law, are delivered via the existing licensing regime.

9.2.1 Regulatory Principles

The fundamental regulatory principles against which the licensing regime should be measured, are outlined in Table 9.1.

Table 9.1: Fundamental regulatory principles against which the licensing regime for the GDF will be judged in this chapter.

1. Clear legal framework	2. Clear and predictable regulatory process	3. Technically competent and independent regulation
4. Regulator power to grant NSL	5. Regulator power to attach conditions to NSL	6. Regulator enforcement powers
7. Appropriate non-compliance penalties	8. Permissioning to construct or operate	9. Fit and proper licensees
10. Licensee responsibility for safety	11. Permissioning to undertake major activities	12. Adequate supporting documentation
	13. Propertionality of supporting documentation	

To ensure the efficient regulation of the GDF, it is advisable that that each of these principles, some of which are bound by international obligation or law, are delivered and demonstrable

prior to NWS' application for a nuclear site licence.

Principle 1: There should be a clear legal framework for the licensing of the GDF.

The existing legal framework for licensing nuclear installations is well established (as outlined in 7.4.2.1), and the application of nuclear site licensing to the GDF would meet Principle 1 [12], [13], [335]. Though the GDFs hazard potential is lower than some other NIs, the active nature of the materials utilised, anticipated for storage and disposal require a clear, stringent framework for licensing to ensure worker and public health is sufficiently protected. NWS and ONR should be fully aware of their obligations and responsibilities in relation to nuclear safety, which is achievable via a clear framework for licensing. The public, politicians and other stakeholders can then be assured that waste is being disposed of responsibly, considering the needs of current and future generations.

Principle 2: The regulatory process should be clear and predictable.

The process for regulating the GDF should be one that both regulators and licensees are able to interpret and apply without unexpected alterations. The scale, cost and risk associated with the development of a GDF are considerable. As such stakeholders need to be assured prior to the commencement of the project that it will be regulated in a way that won't change over time, and will not unexpectedly compromise the progress of the project.

At present, the information provided by ONR on the licensing process and the role of licence conditions is sufficiently thorough and transparent that the licensee and regulator can be fully aware of the regulatory requirements and functions placed upon them, and other stakeholders sufficiently informed, as evidenced by the successful implementation for a number of UK NI [13].

Principle 3: There should be a technically competent and independent nuclear safety regulator.

Under the Joint Convention (see Chapter 5, Section 5.2.1), the UK Government is required to establish or designate an independent regulatory body for the implementation of a legal and regulatory framework [262]. ONR are the UK's independent regulator for nuclear safety, security

and safeguards, established under the TEA13 [335]. They are organised into operational delivery programmes, reflecting the sectors of the nuclear industry they regulate.

The GDF's early development will be driven by community consent, and the independence of ONR will promote transparency, and hence confidence in the integrity of the licensing process. Public and political confidence in the ability and independence of ONR is therefore crucial if the GDF is to be successfully licensed and operated. ONR is regarded as a technically competent regulator with the necessary capability to assess the licensee's safety case and undertake robust regulatory oversight.

Principle 4: The regulator should have the powers to grant nuclear site licences.

The GDF will require a nuclear site licence (NSL) under the NIA65. It's vital that the regulator for nuclear safety is afforded the power to grant a NSL to the operator of the GDF before work begins to ensure an effective and efficient nuclear site licensing process. ONR has the power to grant NSLs for all prescribed activities, including geological disposal if prescribed as in 9.3.1.1. It acts independently and has been instrumental in the establishment of the current licensing regime and requirements, including licence conditions.

Principle 5: The regulator should have the powers to attach conditions to a GDF's nuclear site licence in the interests of nuclear safety and the management of radioactive waste.

As shown previously, the inventory of materials managed on the GDF site contain sufficient residual activity to require substantial regulator oversight. If the ONR was unable to attach licence conditions relevant to safety, its ability to maintain and implement this oversight would be undermined. ONR has the powers to attach conditions to the nuclear site licence under the current legal framework, and this power will continue to be enforced in application of the licensing regime to the GDF.

Principle 6: The regulator should have appropriate enforcement powers, including the power to halt activities in the interests of nuclear safety.

The current regulatory framework provides ONR with multiple levels of enforcement through permissioning, principally through primary and derived powers attached to licence conditions [347]. It is necessary that the regulator is provided with the appropriate enforcement powers to ensure they are able focus their oversight on whichever of the licensee's activities are critical to maintaining nuclear safety across the nuclear licensed site. By providing the ONR with these powers, stakeholders can be assured that, they will impartially (as an independent authority) assert the necessary oversight to ensure nuclear safety is maintained.

There are multiple points from construction through to the backfilling and closure of the GDF where nuclear safety may be compromised, for example failure to deliver against the assumptions set out in the the safety related to the design, construction, commissioning and operation of the GDF could lead to unexpected performance and adverse affects on the health and safety of future generations. The ONR, as regulator, should be aware of any issue that may inhibit safety on site and have sufficient power to intervene where necessary, to request more information or enforce a shutdown of activities pending further action. The current framework provides ONR with the powers to halt operations through LC31 "Shutdown of specified operations".

Principle 7: There should be appropriate penalties for non-compliance.

Under the existing nuclear safety regulatory framework there are a range of penalties for non-compliance. The hazard potential associated with a large majority of radioactive substances activities is sufficiently high that the potential consequences of accidents that could result in the release of radioactivity, or non-compliance with the safety case that could undermine the long-term performance of the GDFs warrant stringent penalties for non-compliance. ONR enforcement activities are largely carried out by its inspectors, and their activities can include providing licensees with advice, warnings, letters, notices and the utilisation of powers provided by licence conditions or under the relevant legislation.

Any person guilty of committing an offence on a nuclear licensed will be penalised [12]. Penalties vary and are tailored to the severity of the offence, but include criminal prosecutions, fines

applied to the licensee and individuals and indirect commercial penalties associated with the shutdown of operations.

Principle 8: A regulatory permission should be required to construct or operate a nuclear facility.

The NIA65 requires that the GDF cannot be constructed without a nuclear site licence. Permission from ONR is therefore required before construction of the GDF can commence. In the development of the GDF, there may be design modifications or plant modifications that could if incorrectly implemented lead to accidents or non-compliance with safety case requirements. It's important ONR is provided the necessary powers to permit these critical activities. Legislation and licence conditions provide the ONR and licensee with flexible permissioning options, including at the points of construction and operation, which will enable the efficient and proportionate regulation of the GDF under the current framework.

Principle 9: Only a fit and proper corporate organisation with the necessary financial and technical resources should obtain a nuclear site licence.

The size and nature of infrastructure projects such as the GDF requires that adequate resources are in place to accommodate for the anticipated cost of the project, as well as any unforeseen incidents or incurred costs. Ensuring the licensee is adequately resourced to develop the GDF and implement disposal is essential to nuclear energy's involvement in the future energy mix in the UK, as well as in the maintenance of the safety standards for the final repository. The current regulatory framework for licensing ensures only a corporate body can be granted a nuclear site licence and ONR has the responsibility to ensure that NWS will be a fit and proper organisation with adequate financial resources.

Principle 10: The licensee should be responsible for nuclear safety.

Despite the ONR's jurisdiction over safety, it should be the responsibility of the licensee to implement the requirements of relevant laws and regulations. If the licensee is not obliged to meet these responsibilities, it could lead to any number of issues including how to penalise issues of non-compliance with safety requirements, and might impact on the safety culture

implemented on site.

The independence of the ONR would be compromised if they were responsible for maintaining nuclear safety when already in charge of regulating safety on the nuclear licensed site. Without this, there would be no way of assuring stakeholders that the management of radioactive waste on a GDF site was being conducted responsibly, or communicated transparently. The current regulatory framework for licensing places legal responsibility on the licensee for the maintenance of nuclear safety on the licensed site, and in application to the GDF, will ensure this rests with NWS. [12], [341], [343].

Principle 11: Permission from the nuclear safety regulator should be required in advance of undertaking major activities that could affect nuclear safety.

There are credible scenarios in which safety measures could be compromised through the decisions made during the GDF lifecycle as discussed in the description of Principle 8. It's sensible therefore that the regulator be afforded opportunities to permission the undertaking of activities which may have an impact on the maintenance of safety on the nuclear licensed site.

ONR currently implement permissioning through the conditions attached to the NSL, which provide them with the primary or derived powers necessary to oversee major activities. As the regulator, ONR has the power to call a licensee's arrangements in for approval and specify that the licensee may not conduct the activity, or the next stage of that activity, without their consent. For example under LC4 for new installations, no nuclear matter may be brought onto the site for the first time without the consent of ONR, or the control of modifications provided to ONR under LC20 and LC22.

Principle 12: Permission to undertake a major nuclear safety related activity should depend upon adequate supporting documentation submitted by the licensee.

The adequacy of a licensee's supporting documentation is vital to the progression of the development of the GDF. The current regulatory framework requires the licensee to produce adequate safety documentation to support requests for permission to proceed with activities

across the lifecycle of the GDF. ONR is responsible for assessing the adequacy of safety submissions and through the powers they are granted, permission activities only when satisfied an adequate safety case has been made. At present this is implemented through the contents of licence conditions, such as LC21 "Commissioning" and LC23 "Operating rules". For the GDF, a unique development in the UK, this will even more critical, in assuring stakeholders that sufficient regulatory oversight is being provided.

Principle 13: The rigour of supporting documentation should be proportionate to the hazard potential of the activity.

It's essential that the hazard potential of the activities conducted on a licensed site is reflected proportionately in the time and effort required in the development and submission of supporting documentation. The GDF, as discussed previously, poses a much lower hazard potential than many other NIs. As such, the substantiation provided by NWS through supporting documentation should be proportionate to the hazards. The current regulatory framework provides the flexibility to enable NWS to tailor its safety documents in a way that reflects the hazard potential and ensure Principle 13 is met.

9.3 Proposed Regulatory Framework

Based on the mapping and analysis presented through Chapters 6-8, Section 9.3 provides an outlined proposal for a proportionate regulatory framework to be applied to the UK GDF.

9.3.1 Nuclear Safety Framework for Geological Disposal

9.3.1.1 Amendments to Legislation, Regulation and Guidance

As discussed in Chapter 8, the Nuclear Installations Act (NIA65) 1965 and Nuclear Installations Regulations (NIR71) 1971, are the overarching legislative tools out of which the requirement for nuclear site licensing was established. The NIA65 states a licence is required for the purpose of installing or operating a nuclear reactor or any other prescribed installation that isn't already covered by a valid nuclear site licence. Those which may be prescribed under Section 1(3)(c) include those:

"designed or adapted for— (c)storing, processing or disposing of— (i)nuclear fuel, or (ii)bulk quantities of other radioactive matter which has been produced or irradiated in the course of the production or use of nuclear fuel."

However facilities for the disposal of HAW, such as the GDF, are not prescribed under the NIR. As such, the primary focus for changes in nuclear safety legislation relate to the issue of defining a GDF as a facility which must be licensed, in accordance with 1(3)(c) of the NIA65. Two approaches to achieving this are outlined below.

Prescription of Disposal Facilities in the Licensing Regime

To ensure UK policy and legislation align, either the NIA65 or NIR71 may be amended to include disposal facilities as licensable facilities. This could be achieved by adding the following (see bold text) to the Nuclear Installations Act 1965 (Section 1):

"(1)No person may use a site for the purpose of installing or operating—

- (a)any nuclear reactor (other than a nuclear reactor comprised in a means of transport, whether by land, water or air),
- **(b) any facility for the disposing of—**
  - **(i) nuclear fuel, or**
  - **(ii) bulk quantities of other radioactive matter which has been produced or irradiated in the course of the production or use of nuclear fuel**
- (c) any other installation of a prescribed kind, unless a licence to do so has been granted in respect of the site by the appropriate national authority and is in force."

This would remove the requirement for a disposal facility to be prescribed under the NIR71 and allow the GDF and any future disposal facility to be eligible for licensing. However, this might also require an amendment to Section 1(3)(c) to remove facilities designed or adapted for "disposing" from the list of installations which may be prescribed. Also, the proposed amendment would not differentiate low-risk disposal facilities (i.e. the near-surface disposal of LLW and VLLW) from those disposing of HAW such as the GDF. This could raise an issue as to whether facilities such as LLWR, which holds a licence for the storage of nuclear matter, would also therefore require a licence for on-site disposal. This is a complex issue due to the positions of the devolved administrations who might see this as a power play by ONR. A change to the NIA65 would also require primary legislation to be passed through Parliament, which would be less time and resource efficient than a change to regulations via secondary legislation.

Licensing the GDF can also be achieved through amendment of Section 3 of the Nuclear Installations Regulations 1971 (NIR71) to include a GDF in the list of prescribed installations, such as:

"(9) any installation designed or adapted for the disposal, below a depth of 200 m underground, of—

- (a) irradiated nuclear fuel,
- (b) higher activity radioactive wastes,
- (c) radioactive waste that is not suitable for near surface disposal."

This would enable the GDF to be licensed without the need to amend the NIA65, whilst also providing for flexibility in future policy decision making by including spent nuclear fuel in the list of potential future wastes for disposal. The proposed amendment specifies a licence is required for geological disposal (below 200m) for a number of specific waste streams, but does not preclude the disposal of these wastes by alternative, appropriate means if any are identified. This might be particularly useful in dealing with some short-lived HAWs which after a period of interim storage, and decay, might be more suitably disposed of in a near-surface facility.

A more specific description of the waste which may be disposed of in a GDF, as proposed in this amendment (to NIR71), might also overcome the issue of bulk quantities of radioactive matter, or nuclear matter, for radioactive waste disposal. However a revised interpretation of bulk quantities of radioactive matter, as discussed below, will also allow the NIR71 to be easily amended to ensure a GDF and the waste consigned to the site can be covered by a nuclear site licence.

The inclusion of a geological disposal facility in the list of prescribed facilities under the NIR71 would be less intensive on resources, time or cost, than amending primary legislation (NIA65), and may therefore be considered the more favourable option of these two proposed amendments.

"Bulk Quantities" of Radioactive Matter

ONR have considered two options for defining bulk quantities to ensure proportionate regulation of future disposal facilities in the UK. The adoption of a single interpretation of bulk quantities applied to both storage and disposal facilities, and separate definitions with limits to be applied specifically to sites for storage and disposal, was consulted on in 2020 [337].

The existing interpretation quantifies bulk quantities as matter exhibiting activity levels at

or above one hundred times those set out in the Radiation Emergency Preparedness and Public Information Regulations 2019 (REPPIR) [340]. A position statement in November 2021 confirmed a revised interpretation that would allow for separate definitions of bulk quantities when applied to storage and disposal, to accommodate for the size and associated activity of a GDF [400]. This states "A site licence will be required for the installation and operation of a disposal facility if it is designed or adapted to dispose of quantities of radioactive matter at or above 1 million times the REPPIR level.". This is a sensible approach as it will ensure a GDF and any future contents (with or without SNF disposal) assuredly align with the requirements of the NIA65 and NIR71 whilst excluding disposal facilities for lower activity wastes from statutory licensing obligations.

9.3.1.2 The Role of Licensing in the Siting of a GDF

Government responsibility for siting policy in England is held by the Department for Business, Energy and Industrial Strategy (BEIS). It's down to NWS to satisfy itself that a site is consistent with the Government's siting policy before applying for planning permission. ONR, as the regulator for nuclear safety, will assess the suitability of a site, through the relevant preliminary safety submissions (e.g. the PCSR, see Section 9.2.2) against its Safety Assessment Principles (SAPs). The SAPs are shaped by IAEA safety requirements for siting and will also consider factors such as local demography and the engineering and infrastructure requirements of the facility [349].

ONR is not responsible for making site selection decisions, and a nuclear site licence for the GDF may not be issued until the point at which construction critical to nuclear safety commences. ONR will provide expert advice on and scrutiny of early work in the site selection process, but remain independent of decision making to enable the GDF-specific, voluntarism based site selection process to culminate [19]. Once licensed, all standard licence conditions will apply, with construction controlled under LC19 "Construction or installation of new plant" and LC20 “Modification to design of plant under construction” empowers the ONR to approve any changes

to the design which may affect safety on the selected site, during the construction period [346].

9.3.1.3 The Nuclear Site Licensing Process

The process for licensing nuclear installations in the UK was outlined in Section 7.3.2; this described a step-like procedure, placing actions on the regulator and licensee from pre-application through to decommissioning and closure. How this might be implemented for a one-off GDF is summarised in Figure 9.2. ONR will administer and regulate the granting of the nuclear site licence to the applicant (NWS), when they are satisfied with their management prospectus and pre-construction safety case.

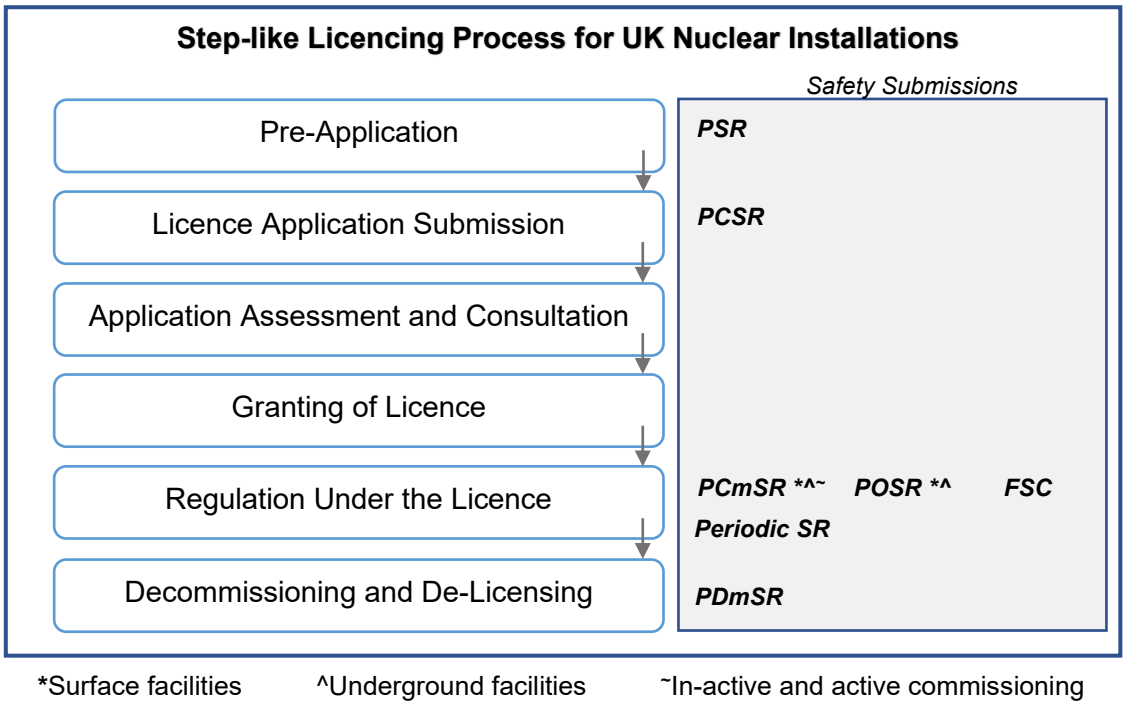


Figure 9.2: The step-like licensing of UK nuclear installations, which should be applied to the Geological Disposal Facility (GDF).

In principle, the fundamental stages of the licensing process need not change when applied to the GDF. Good practice would be for NWS to develop a regulatory schedule with the ONR, which sets out the key hold points in the licensing process such as commencement of construction,

inactive commissioning , first waste receipt, active commissioning, commencement of routine operations etc. and the necessary supporting safety documentation. This regulatory schedule should be developed commensurate to the hazards associated with the GDF, as such the number of safety submissions could differ compared to those expected for nuclear installations with higher hazard potentials [349]. Figure 9.2 provides a high level indication of the safety submissions which would adequately meet the regulatory requirements for the GDF. The production of a Preliminary Safety Report (PSR) would provide the foundations for each of the in-depth safety submissions that follow, and is where the licensee will set out its design philosophy, concepts, site characteristics and justifications for the GDF. The intention of the PSR should be to show that there are no safety "show stoppers" and that there is confidence that the more detailed PCSR, which is required as part of the licensing process, can be achieved.

Once a licence has been granted, the primary powers provided to the ONR through conditions attached to the NSL will aid ONR and NWS discussion over appropriate hold points in the development of the GDF. At each stage, the licensee will be required to obtain the permission of ONR to proceed. This will only be granted when ONR is satisfied with the adequacy of the documentation to justify the safety of the proposed activity [346]. The management of the permissioning process will be most efficiently achieved through the implementation of a regulatory schedule as discussed above, of safety submissions which demonstrate that the licensee is capable of delivering the phases of the GDF's development, with due care to safety. In relation to safety, the key stages in a GDF regulatory schedule would be:

- Preliminary Safety Report (PSR)- enables licensee to commence dialogue with ONR around the prospects of a proposal being successful (i.e. licensable) and allow ONR to prepare regulatory resources required to regulate the project.
- Pre-Construction Safety Report (PCSR)- to demonstrate that the GDF's design meets safety objectives, through analysis and substantiation, and provide confidence in management systems and strategies, prior to commencing construction. The PCSR will apply to the entire GDF site.

- Pre-Commissioning Safety Report (PCmSR)- to outline a programme of commissioning for all systems and equipment related to safety, which establishes their safe operation in accordance with all safety claims. This will need to consider how and when commissioning occurs in operational areas whilst construction occurs congruently in other areas of the site, including where necessary hold points where one activity could impact on the outcome of another. PCmSR for inactive and active commissioning will be required for surface and underground facilities.

- Pre-Operational Safety Report (POSR)- to demonstrate the facility as-built meets safety criteria and is capable of safe operation (including a summary of commissioning results), including the establishment of plant operating rules and operating instructions commensurate to regulatory requirements. A POSR will be required for the surface facility, first underground galleries and subsequent galleries.

- Facility Safety Case (FSC)- a living document comprising the totality of all aforementioned safety submissions, updated throughout operation, which demonstrates that safety criteria are being met, identifies conditions and limits necessary in the interest of safety, and demonstrates compliance with limits and legal duties for risk reduction throughout operating procedures.

- Pre-Decommissioning Safety Report (PDmSR)- which demonstrates that the underground facilities can be decommissioned safely prior to final closure, and that surface facilities can be decommissioned safely by progressive and systematic reduction in hazard (where necessary/possible) through decommissioning tasks and objectives. Should also define safety goals and criteria for decommissioning tasks and that the appropriate infrastructure and resources are in place to ensure decommissioning tasks are carried out as intended.

- Periodic Safety Review- As well as scheduled submissions, NWS as the licensee will be required to produce periodic safety reviews every 10 years (subject to negotiation) in accordance with the conditions of the NSL.

The length of time associated with the operational and decommissioning phases of the GDF, requires safety submissions will need updating to reflect events or incidents, changes in strategy or improved knowledge, or at each hold point (where staged operation or decommissioning is being implemented) to ensure the safety case remains valid throughout that stage of the development.

9.3.1.4 Appropriate GDF Nuclear Site Licence Conditions

The analysis conducted in Chapter 8 evaluated the applicability of the current licensing framework to a prospective geological disposal facility. Having evaluated all of the 36 standard licence conditions (LCs) that are attached to nuclear site licenses, this section addresses which should be attached to the licence for the GDF. From the analysis in Chapter 8, it was also drawn that there were a couple of fundamental issues which are specific to the first and possibly one-of-a-kind GDF, which would be sufficiently addressed through the licensing framework: 1) defining the site boundary and 2) the representation of the underground footprint in safety submissions. How these may be addressed, if necessary, is outlined below.

Definition of the Licensed Site in the Context of a GDF

As discussed in 8.3.2.1, it would be inappropriate to require physical demarcation of the boundary of underground facilities on the surface, but may be plausible to amend the LC to address the GDF's underground boundary, without duplicating the requirements of other LCs.

It would be appropriate to amend LC2(4) to ensure all areas, including those where the LC at present is not practicable (i.e. underground), are still covered. As there may not be means of marking the underground boundaries, a tweak to the language used in LC2(4) could accommodate non-physical demarcation, such as:

"4. The licensee shall mark the boundaries of the site by fences or other appropriate means, and where no appropriate means exist, ensure adequate access to site plans produced in accordance with Condition 16 of this schedule at appropriate locations on the licensed site. Any such fences

or other means used for this purpose shall be properly maintained."

This would provide the licensee with the option of justifying to the regulator whether it is practical to mark the boundary, and where it's not, how they will ensure underground facilities are not excluded from the requirements of LC2(4), by making the site boundary (set out in site plans under LC16) readily available at appropriate locations, such as the entrance to the GDF's underground facilities. The ONR's SAPs could be amended to reflect what appropriate means for physically marking the boundary are or how to determine whether those means exist.

Alternatively, as mentioned in 8.3.3.2, it would also be possible to disapply LC2(4) on certain parts of the GDF site. This could be favourable as it would ensure no tangible changes are required to LC2, which might otherwise complicate the application of LC2 to some other nuclear installations.

The 3-D Underground Footprint

Under LC16(1) the licensee is required to "submit an adequate plan of the site showing the location of the boundary of the licensed site and every building or plant on the site which might affect safety". As with LC2(4), the unique nature of the GDF's underground footprint and it's lateral extent, outwith the surface site boundary, creates an issue over what an adequate plan of the site should look like. The underground workings won't be easily represented by conventional two-dimensional descriptions, as the layout is not likely to be so uniform that a cross section would accurately describe the extent of the repository in all directions. Crucially, the wording of LC16 allows the licensee to interpret what constitutes an "adequate" plan of the site, which might contain a series of two-dimensional layers, three-dimensional representations or a combination of the two. As such LC16 may be attached to the licence for a GDF in its current form; it is recommended that the ONR's SAPs to provide inspectors guidance on how to assess three-dimensional site plans, as well the development of further guidance to define the legal boundaries of the licensed site.

Licence Conditions

Chapter 8 demonstrated that all of the 36 standard LCs are applicable to the regulation of a GDF without significant requirements for amendment, sentiment shared by the ONR in its assessment of the current requirements [270]. Many of the GDF-specific issues raised throughout the analysis may be addressed through the licensee's arrangements under the LCs, meaning amendments to most LCs would not be required. Based on the analysis conducted in Chapter 8, I propose that all 36 standard licence conditions should be attached to the Nuclear Site Licence (NSL) for a GDF in England or Wales. Minor amendments to a number of conditions, specifically with the licensing of geological disposal in mind, along with a new prospective licence condition, are discussed herein.

Proposed Amendments to Licence Conditions for the GDF's Nuclear Site Licence

Licence Condition 1- Interpretation

All of the definitions contained in LC1 will apply to the GDF, as specified in Section 8.3.2.1. Once a GDF has been prescribed as a licensable activity, it would however be appropriate to include a definition for disposal, to aid the implementation of conditions which refer to disposal (e.g. LC33), and could read:

"Disposal" refers to the final emplacement and backfill of waste in a geological disposal facility or consignment to conventional landfill or near-surface disposal facilities, as appropriate for the classification assigned to the waste, with no intention to retrieve the waste once emplaced."

This may however require further reference or clarification to be made as to the classification of the UK's radioactive waste. Alternatively ONR could update the definition of "operations" to account for disposal activities such that it reads:

"operations" includes maintenance, examination, testing and operation of the plant and the treatment, processing, keeping, storing, accumulating, disposal, or carriage of any radioactive material or radioactive waste and "operating" and "operational" shall be construed accordingly; "

which would ensure a distinction between emplacement and disposal is not required.

Licence Condition 2- Marking the site boundary

As discussed, there's scope for amendment of LC2(4) with respect to the underground areas of the GDF site, though it would be advised that disapplication of LC2(4) may be favourable in specific areas of the GDF site where it cannot be practically applied (i.e. the underground footprint of the GDF).

Licence Condition 30- Periodic Shutdown

As discussed in 8.3.2.1, the periodic shutdown of a plant for the purpose of EIMT places a potential hold point on the licensee, where under LC30(3) ONR can specify it must consent to the re-commencement of the plant/processes involved. Given the low hazard potential associated with the disposal of HAW, the primary powers afforded to the ONR may not be befitting to many of the EIMT activities requiring periodic shutdown and would be better reflected through derived powers/licence instruments. Where activities do pose particular safety risk, the primary powers may still be applied. LC30(3) could be amended (as below) to reflect the nature of the risks/hazards such that it reads:

"The licensee shall make and implement adequate arrangements to ensure that when a plant or process is shut down in pursuance of paragraph 1 of this condition it shall not be started up again thereafter without the consent of ONR, if in the interests of safety."

An amendment of this nature would provide the licensee more flexibility in their ability to judge the severity of the risks posed by a plant shutdown for EIMT and whether ONR permissioning provides the best means of regulatory oversight. Through the "adequate arrangements", a separate mechanism for ONR involvement in activities associated with lower risks could be established and maintained for non-safety related issues identified. ONR may consider it unnecessary to stipulate safety specific permissioning under LC30, on account of the consideration for hazard potential the licensee is afforded through the making of their own arrangements. As such, it might be preferable that regulatory guidance is produced to inform licensees and inspectors of circumstances by which the permissioning of a shutdown is necessary and proportionate.

Additional Licence Conditions for the GDF's Nuclear Site Licence

Many national programmes include provisions for the retrieval or reversibility of waste disposal, for a limited timeframe, or at any point in the future. It will fall to policymakers to decide whether the UK will mandate a period of waste retrievability. Should the UK Government decide to do so, this may be implemented through an additional licence condition and might read:

"Licence Condition 37: Retrieval of radioactive waste

The licensee shall ensure that any radioactive waste disposed of, in accordance with an environmental permit, is retrievable for a period of 50 years, or such other periods as ONR may specify, in the interests of safety."

Implementing such a condition may be difficult in practice, whilst the propensity for retrievability to increase risk has previously formed the basis for EA and Nuclear Installations Inspectorate (NII) opposition when addressed by CoRWM [16]. However building in a requirement for retrievability could prove beneficial in gaining public and political acceptance of the GDF, whilst providing the licensee the flexibility, in the event of significant scientific advancement, faults in the employed disposal methods or changes to UK policy. Its inclusion would empower ONR to specify whether retrievability should be factored into the GDFs development, and to specify a timeframe over which it should be applied. If retrievability is re-visited, ONR will need to consider if it can lawfully attach this type of condition and if it would sufficiently relate to aspects of safety, security or safeguards. It would also need to be considered whether a licence condition pertaining to retrievability contradicts any definition of disposal which requires there to be no intent to remove waste once emplaced. Given the current division of roles and responsibilities set out under the MoU, it may also be an option for a condition of this nature to be included instead as part of the environmental permit authorising disposal in the GDF.

9.3.2 Environmental Protection Framework for Geological Disposal

9.3.2.1 Amendments to Legislation, Regulation and Guidance

As discussed in Chapter 8, the environment agencies have devised a tailored, two-part permit application process for specific activities including the use of sealed radioactive sources and on-site burial of radioactive waste, which should be perfectly applicable to the permitting of a geological disposal facility. The REA provide guidance as to how to submit the relevant application forms, to aid the efficient assessment of submissions.

However one area in which the framework as whole could be improved is in the updating of guidance to better reflect current legislation. The Guidance on the Requirements for Disposal Authorisation 2009 (GRA) was put together at a time the Radioactive Substances Act 1993 (RSA) applied to all nuclear installations in England, Wales, Scotland and Northern Ireland. The first iteration of the EPR superseded the RSA in England in Wales as of 2010, as such the legal framework, powers and duties referred to in the GRA no longer apply implicitly to a GDF in England and Wales, and require adaptation in line with more recent guidance, such as the Guidance on the Requirements for Release from Radioactive Substances Regulation 2018 (GRR).

9.3.2.2 The Environmental Permitting Process

As described in Section 8.4, the regulatory framework for environmental protection for the disposal of radioactive waste is well established. In the EA's Guidance on Requirements for Authorisation (GRA), a staged regulatory approach for the GDF is proposed for the implementation of environmental permitting, from the point of intrusive investigation through to surrender of the permit, as in Figure 9.3 [259].

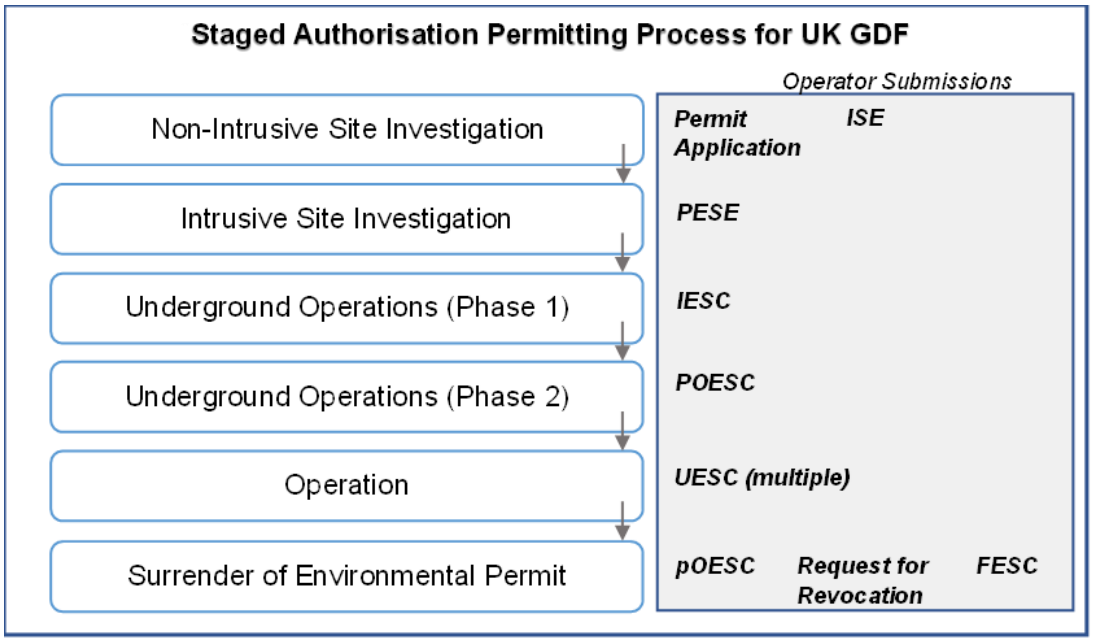


Figure 9.3: The "staged authorisation" of environmental permitting for the UK Geological Disposal Facility (GDF).

The staged authorisation implemented by the REA will best achieved through NWS' submission of environmental safety documents at hold points throughout the GDF development process. Under the MoU between the REA and ONR, the schedules for submission should be coordinated to avoid undue burden on the operator or significant disruption in the progress of the GDF's development. Once the REA is satisfied with the operator's submissions, an environmental permit (initial or revised) may be granted. Based on the GRA, submissions contained in NWS' schedule should include [259]:

Initial Site Evaluation (ISE)- which presents mostly qualitative arguments of the feasibility of construction the GDF at the proposed site, and whether/how the facility would meet the principles of the GRA. Hold point prior to the granting of an environmental permit for intrusive site investigations to commence.

Preliminary environmental safety evaluation (PESE)- provides a combination of qualitative and supporting quantitative assessments based upon site knowledge and data acquired through

initial site investigations. Production of the PESE should coincide with a hold point prior to early phase of underground operation ("Phase 1" in Figure 9.3), for the purpose of obtaining additional information in developing the environmental safety case.

Initial Environmental Safety Case (IESC)- to provide evidence to inform the EA's decision on whether to grant authorisation for disposal in principle. Required at the hold point prior to more substantial underground operation ("Phase 2"), including major construction.

Pre-Operational Environmental Safety Case (POESC)- generated to demonstrate the disposal system meets the principles and requirements of the GRA, based on sound scientific and technical basis, which would aid the decision to grant a revised authorisation for radioactive waste to be placed in the GDF. Hold point prior to final waste placement in the GDF.

Updated Environmental Safety Case (UESC)- once the environmental permit for disposal has been granted, the length of the operating period for disposal ensures periodic review of authorisation, including updates to the environmental safety case at agreed intervals.

Post-Operational Safety Case (pOESC)- once waste emplacement has ceased, the pOESC will need to demonstrate that the facility will be closed in a way consistent with the principles and requirements of the GRA. Provides a hold point to facility closure and operator's application for permit revocation, which will be submitted alongside a Final Environmental Safety Case (FESC).

9.3.2.3 Appropriate GDF Environmental Permit Conditions

As discussed in 8.4.3, analysis of the generic conditions attached to environmental permits for disposal activities showed minimal amendment is required to apply them to the permit for the GDF (post-permitting for site characterisation). As such, the regulatory framework for environmental protection, as it is currently set out, with a tailored approach including one specific to disposal, should be applied to the GDF in its current format.

Notably, conditions attached to the permit for the Low Level Waste Repository (LLWR) included provisions related to the condition of waste accepted onto the site, including visual inspection of non-enclosed waste packages upon arrival on the permitted site. HAW arriving on the GDF site will arrive enclosed in shielded or transport containers, and subject to regulator authorisation prior to consignment to the GDF site. As such, visual inspection may be more difficult to implement on packaged HAW, and potentially unnecessary given the waste will have been authorised by regulators for transport to the GDF. Nonetheless, if damage in transit is considered a possibility, this type of condition would be considered relevant and appropriate.

Environmental permit conditions are typically categorised as outlined in Table 9.2, and it is wholly appropriate that the same applies to the environmental permit authorising the disposal of radioactive waste in the GDF.

Table 9.2: The proposed categories for conditions attached to an environmental permit for a GDF. Those marked with a * indicate amendments to the current form of the permit conditions have been recommended.

Condition Type	Description
Management	Conditions for the general management of the permitted site, including management systems and environmental safety case development. (1.1.1-1.1.5).
Operations*	Conditions for the control of operations on the permitted site including what activities are permitted and the use of best available techniques (BAT) (2.1.1-2.6.5).
Disposal*	Conditions specific to the disposal of radioactive waste including references to limits for disposal and directions to waste consignors (3.1.1-3.1.9).
Monitoring	Conditions which set out the requirements on the operator for taking samples and measurements for environmental monitoring (3.2.1-3.2.6).
Information	Conditions which cover record keeping and notifications (4.3.1-4.3.8).

Amendments to Conditions for the GDF's Environmental Permit

Herein, amended or additional conditions are proposed for attachment to the environmental permit for the GDF, based upon the research reported in Chapter 8.

Operations Conditions

Condition 2.3.3

As discussed in 8.4.2.1, the operator is required to use BAT to deliver the outcomes of 2.3.1 and 2.3.2, including the removal of suspended solids from oils which are radioactive and require incineration. As it is not foreseen that such oils will be generated on the GDF site, it might be better to exclude this requirement from Condition 2.3.3 such that it reads:

"2.3.3 The operator shall use the best available techniques to:

- *(a) exclude all entrained solids, gases and non-aqueous liquids from radioactive aqueous waste prior to discharge to the environment;*
- *(b) characterise, sort and segregate solid and non-aqueous liquid radioactive wastes, to facilitate their disposal by optimised disposal routes;*

Disposal Conditions

Condition 3.1.8

Having established waste received on the permitted site meets the specifications set out to consignors, there should be procedures set out in the WMP for the acceptance of waste for disposal. NWS will be assured that the wasteforms for disposal are as safe as is reasonably practicable to dispose of. This will be achieved through the development and implementation of waste acceptance criteria (WAC), informed by NWS' Disposability Assessment and Letter of Compliance (LoC) procedures. The permit for LLWR addresses this in condition 3.1.8:

"3.1.8 The operator shall only dispose of solid radioactive waste by burial if: (a) all the relevant

radioactive waste acceptance procedures have been completed and it fulfils the relevant radioactive waste acceptance criteria as defined by the environmental safety case, unless otherwise agreed in writing by the Environment Agency; (b) it has not been diluted or mixed solely to meet condition 3.1.8(a) or any other condition of the permit."

Given the inherent activity and long-lived nature of many of the radionuclides within the HAW to be disposed of in the GDF, compliance with WAC shall be even more critical in some respects to the long-term environmental safety case than LLW. As such it's justified that this should be reflected in the conditions attached to the environmental permit for the GDF. Clarity should be sought by NWS as the operator as to whether vitrified HLW contravenes 3.1.8 (b) with respect to dilution of waste, given the nature of HLW conditioning and waste loading considerations during wasteform production.

9.3.3 Security Framework for Geological Disposal

9.3.3.1 Amendments to Legislation, Regulation and Guidance

As set out in Chapter 7, the regulation of security on nuclear licensed sites is governed by the Nuclear Industries Security Regulations 2003 (NISR), under the jurisdiction of the ONR. Highlighted in Section 8.5.1, some ambiguities in the terminology utilised in legislation raise questions as to the applicability of the NISR to the GDF site in its entirety. Minor amendments would ensure unequivocally that the NISR are applied to the GDF as any other NI.

"Nuclear Premises"

Nuclear sites are defined in the ATCSA as those holding a nuclear site licence under the NIA65, which a GDF will hold. Nonetheless, the primary security regulations (NISR) only refer to sites which use or store radioactive materials, failing to address the primary purpose of the GDF-disposal. Therefore it's difficult to quantify if the NISR only apply to areas of the licensed site involved in the storage of radioactive waste, or the entire GDF site.

With minor amendment, the definition of "nuclear premises" could better reflect the applicability of the regulations to a GDF, for example to read:

" *"nuclear premises" means—*

"(a) a nuclear site on which nuclear material or other radioactive material is used, stored or disposed of;"

By making a change such as this the NISR could continue to be applied as it is currently, across the entirety of the nuclear licensed site for the GDF, without uncertainty as to whether security should be regulated in the same way for the underground facilities as they are for those at the surface.

"Nuclear Material"

At present, the NISR defines nuclear materials in accordance with the ATCSA, which refers to the definition in The Energy Act 2004, as outlined in Section 8.5.1.

If the GDF was dealing with the disposal of SNF, Pu, or U, the NISRs would apply as "nuclear material" would be present on the premises. The HAW destined for the GDF, conditioned, passively safe HAW wasteforms, is not as of yet prescribed in the NISR's schedule or in regulations by the Secretary of State. Amendment of the NISR to accommodate radioactive waste as "nuclear material" would remove any ambiguity as to the applicability of the NISR to the wasteforms for disposal in the GDF. The primary place for prescription of radioactive waste may be under regulation 3 "Meaning of "nuclear material", "Category I/II nuclear material" and "Category III nuclear material"".

In essence, the application of the existing framework for regulating security on UK NIs should be suitable for the GDF provided disposal facilities and HAW are prescribed under the NISR.

9.3.4 Safeguards Framework for Geological Disposal

The research conducted as part of Chapter 8 on the UK's existing framework for the regulation of safeguards issues demonstrated it to be suitably applicable to the GDF. Material accounting techniques are well established, and should be combined with a highly coordinated system of containment, surveillance and monitoring to verify the movement of materials within the surface site boundary, and when moving between the surface and underground facilities[401].

As previously discussed, it's possible that the GDF will be required for the disposal of HAW and spent fuel, some of which is categorised by the IAEA as safeguarded and some which is non-safeguarded. As a result, NWS would be advised to implement additional or novel monitoring activities to distinguish the movement of safeguarded materials, which they should be able to do through its arrangements under safeguards regulations, and IAEA safeguards in their existing form.

9.3.5 Regulatory Interface

Based on the arguments presented in Chapter 8, the challenges associated with the joint regulation of a geological disposal facility are clearly established. Regulators with different remits for oversight share a number of areas of interest to which they apply their own regulatory requirements, and they utilise the Memorandum of Understanding (MoU) to ensure licensees/operators are not subjected to duplicate requirements in these areas.

Many stakeholders in the survey identified clear and sustained communication between the regulators as the best means of avoiding or resolving conflicts of interest where the ONR and REA place requirements on the licensee/operator. The primary challenge with joint regulation comes in coordinating regulatory activities and ensuring compliance with one regulator does not breach the expectations of the other. However, no challenges associated specifically with geological disposal were identified throughout the research conducted in Chapter 8 to indicate

that the adoption of a single regulator for the regulation of the GDF is required. As such the MoU, in enforcing inter-regulator dialogue and consultation, and enabling the regulators to clearly establish their roles and regulatory responsibilities, should suffice in application to the GDF if adhered to suitably. The enforcement of permitting will commence prior to the requirement for nuclear site licensing, so it's key that channels for clear communication are established at the earliest point possible. For example, NWS should consult with ONR throughout the development of the PSR, prior to the formal licensing process.

As shown in 8.7, the merits of adopting a single regulator in response to the challenge of regulating the GDF don't necessarily outweigh the drawbacks, in terms of the impact it could have on the regulation of other joint regulated sites across the UK (particularly in devolved administrations). As such continuous preservation and refinement of a productive and efficient relationship should be the primary concern of ONR and the REA in the regulation of the GDF.

Chapter 10

Summary and Recommendations

The aim of this project was to explore the safety and regulation of a GDF for the UK's higher activity radioactive wastes located in England or Wales, and to draw some conclusions on the appropriateness and efficacy of the existing regulatory framework for nuclear installations in the UK.

Research covered the characteristics of radioactive waste, disposal methodologies, geological settings, engineered barriers, nuclear safety cases including risks to future generations, land use planning, environmental permitting, nuclear site licensing and the impact of and on Government policies. National programmes and approaches from across the globe have been outlined to allow for comparison with the approach taken, primarily in the regulation of nuclear safety and implementation of nuclear site licensing, in England and Wales.

Finally, the project examined the various regulatory challenges associated with geological disposal and provided an evaluation of the regulatory framework to effectively control the design, construction, commissioning, operation, and closure of a GDF in England or Wales.

10.1 GDF Safety Issues

10.1.1 Geological Settings and the GDF

The UK's geological disposal facility will be located in one of three generic geological settings, high strength rock (HSR), lower strength sedimentary rock (LSSR) or an evaporite environment, as discussed in Chapter 2. Each setting is associated with distinct benefits and drawbacks. HSRs, are strong enough to excavate on the scale required for the GDF without requiring significant structural support and are being utilised as part of Finland and Sweden's implementation of geological disposal. LSSRs promote an alkaline environment which may help prolong the corrosion resistance of other engineered barrier materials, and demonstrate a "self-sealing" of fractures which restricts groundwater flow to diffusion through the geology, and LSSRs have been investigated for use in disposal programmes in Belgium, France and Switzerland. Evaporites similarly creep to close fractures, and provide an extremely arid environment in which little to no groundwater flow is expected, and have been utilised for disposal in the US as well as being investigated as a potential repository host in Germany. Evidently there is a case for the utilisation of each generic geology, however it may also be pointed out that the hardness of HSRs make it prone to fracturing, which will encourage advective flow of groundwater through to the GDF, that LSSRs are mechanically weak and will require some form of structural support to make the GDF safe for workers, whilst evaporites are high in chloride which could be detrimental to other engineered barriers, as well as subsisting as a natural resource which may be sought by future generations.

The implications on regulatory oversight therefore lie in the suitability and feasibility of delivering a GDF on the site, to a design which is demonstrably safe for workers, the public and the environment, both now and in the future. Though regulators will not make the decision as to which geological setting the GDF is located in, they will have significant influence through the feedback they provide to NWS in the early phases of site investigation. Whichever geology is present on the selected site for the GDF will need to be justified in spite of potential drawbacks,

as failure to acquire regulator support would reduce the likelihood of the site being licensed or permitted for geological disposal.

10.1.1.1 Engineered Barriers

The research reported in Chapters 3 and 4 identified the roles and expected performance of engineered barrier materials that may be utilised as part of the GDFs engineered barrier system (EBS). The EBS can be broken down into three primary elements, the wasteform, waste disposal container and backfill/buffer materials, each of which are selected to perform functions specific to the waste stream for disposal and geological setting of the GDF. Wasteform materials such as borosilicate glass (HLW) and cement (ILW) primarily act to physically encapsulate or immobilise the harmful radionuclides contained in the HAW, to generate a chemically stable, irradiation tolerant wasteform, whilst also providing some resistance to erosion by groundwater once surrounding barriers have failed. This can help reduce the rate at which radionuclides are released from the HAW into the GDF, geosphere and over the longer term, the biosphere. Container materials are utilised to provide a second physical barrier, to contain HAW in the GDF for a significant period of time through corrosion resistance or tolerance, which should allow for significant radioactive decay of many harmful radionuclides. Materials such as stainless steels (ILW disposal container) and copper (proposed HLW container) exhibit low corrosion rates (i.e. < 1 μm.yr^{-1} for copper), whilst concrete and carbon steel containers are also being utilised or considered due to favourable mechanical properties, and an ability to shield from irradiation. Buffer and backfill materials may combine primary roles, occupying void space between the container and geological setting, which restricts groundwater flow through to the disposal container, whilst in some cases also maintaining a favourable chemical environment. Cements buffer the pH of the local environment to ensure alkaline conditions, which can help preserve disposal container materials and reduce the solubility of specific radionuclides, whilst also providing a low permeability environment which restricts groundwater flow to the GDF. Bentonite similarly buffers to alkaline conditions, and its mineral composition causes it to swell

when saturated, closing any additional void space, again restricting groundwater flow to diffusion. The highly porous nature of bentonite also enables a proportion of harmful radionuclides to be absorbed once released from the wasteform. In evaporites, crushed rock salt will be used to backfill disposal galleries, homogenise with the surrounding geology and ensure an extremely arid, low permeability environment is maintained.

Each of the engineered barriers performs functions which will promote long-term safety through the restriction of groundwater flow, increasing the time taken for groundwater to contact waste constituents or restricting the release of radionuclides. From a regulator perspective, it will be important that the roles and performance of engineered barrier materials selected meet the expected standards set out in NWS' safety case. This might require more stringent regulator oversight of processes throughout the manufacture, transport and emplacement of EBS materials, which may be conducted through NWS' arrangements for compliance with licence or permit conditions.

The roles and performance of a number of prospective engineered barriers to be utilised in a UK GDF were highlighted in Chapter 4. Evidently, some engineered barriers will be capable of performing a number of important safety functions, providing defence-in-depth to prevent the radionuclides in the radioactive wastes migrating into the geosphere, whilst also delaying the access of groundwater to the radioactive waste enabling the radioactivity to decay.

The combined affect of the engineered barriers on the lifetime of the GDF (that is, the time before which radionuclides begin to be released) will depend ultimately on the geological setting, the waste stream and the properties and cohesion of the materials utilised as part of the multi-barrier system. Data relative to the favourable properties of wasteform, disposal container and buffer/backfill materials were analysed and reported in of Chapter 4, to understand why they are suitable for the UK GDF and the impact they might have on high-level estimates of the GDF's lifetime (i.e. the time over which radioactivity reaches the biosphere and the associated radiological risk to exposed people). Based on the studies reviewed, it's possible the EBS could provide containment of some important radionuclides for a significant period of time. A range

of 35,000–3.5 million years may be anticipated for ILW disposal concepts, 135,000–4 million years for vitrified HLW wasteforms and should it be disposed of in a GDF, 71,000–3 million years for SNF. In the earliest stages of the GDF post-closure period, the backfill will likely be most important to GDF lifetime, slowing and/or buffering incoming groundwaters to reduce the corrosion probability of canister materials. Once the disposal container has been breached, matrix dissolution will dictate the rate of radionuclide release. Based on these high level estimates, a combination of these candidate barriers should suffice in instilling public confidence that a GDF will provide high levels of safety for at least tens of thousands of years, which concurs with conservative safety assessments. NWS will need to demonstrate that engineered barrier materials, selected specific to the design and geological setting, are capable of delivering the safety arguments presented in their safety case submissions to the regulators. Where these arguments are heavily reliant on the barriers meeting performance expectations, regulators may, as discussed previously, need to provide stronger oversight over the evidence provided to support claims of material performance or issues of quality assurance in their manufacture and emplacement in the GDF.

Hence, in order to provide public assurance in the long-term post-closure safety case for a GDF, work is required to reduce the uncertainties in the predicted behaviour of whichever barrier materials are selected, under GDF-specific conditions relevant to the site that's eventually chosen to host the UK's disposal facility.

It is important to note the results of literature surveys indicate the engineered barriers will provide significant protection against radionuclide release, total system modelling should be employed to more accurately describe the combined performance of these barriers, and the rate at which radionuclides will be released.

10.1.1.2 Risk Analysis of Geological Disposal

In Chapter 5, the development and implementation of a 1-D GoldSim model modelling radionuclide release from spent AGR fuel in a hypothetical clay geological setting was described.

Analysis of the base case scenario indicated that the annual risk to a member of a potentially exposed group (PEG) was on the order of $\sim 2.3610^{-8}.\text{yr}^{-1}$, i.e. a 1 in 42 million chance of death due to radiological release, significantly lower than the $10^{-6}.\text{yr}^{-1}$, or 1 in 1 million chance of death, set out by Environmental Regulator's as a suitable risk guidance level (RGL).

A number of the engineered or geological barrier's physical and chemical properties were varied, including bentonite thickness, SNF dissolution rate, disposal container failure time and the sorption capacity of engineered and geological barriers, to identify where the risk posed to PEGs was sensitive to each of these parameters. The results of these sensitivity studies indicated that the predicted annual radiological risk was in general insensitive to most parameter variations. The results of the sensitivity studies indicated the impact the choice of geology may make; as the host geology groundwater flow was dominated by diffusion, it's probable that the impact of the sensitivities, such as the time of container failure or sorption of radionuclides to the bentonite buffer, was masked by the slow migration of groundwater in the geosphere. Decreases in the thickness of the bentonite buffer and an increase in the dissolution rate of the spent fuel matrix were the material properties which had the largest effect on peak observed risk, with peak radiological risks of $\sim 2.6\times10^{-8}.\text{yr}^{-1}$, and $\sim 3.5\times10^{-8}.\text{yr}^{-1}$ respectively, but at no time did the predicted risks breach the RGL. The peak risk was also observed to fall substantially where the natural discharge of groundwater was implemented as the only viable pathway for radionuclide release to the biosphere. This may be a significant factor in countries where geological settings of this nature may exist, however it's not envisaged the UK contains any environments in which only a single pathway could exist for over 100,000 years.

Variation of the GDFs depth appeared to induce the largest increase due to any single sensitivity simulated. When reduced from a depth of 500 m to 200 m, the peak radiological risk observed in

the first 1 million years was ∼3x larger than the base case scenario, at ∼7.5×10^{-8}.yr^{-1}. Whilst this seemed to indicate the selection of depth could be critical to the safety of the GDF, it is important to remember that in reality, this will depend heavily on the make-up of the geological setting ultimately selected for the GDF, and that the level of risk posed still fell well below the RGL. Analysis of a "Worst parameter scenario" demonstrated that under the model's simplified conditions, the level of risk posed by the disposal of AGR SNF in a LSSR also remained below the RGL (peak risk ∼ 1.5×10^{-7}.yr^{-1}), reinforcing the conclusion that a GDF in a LSSR geology presents a tolerable level of risk to future generations. If a more detailed, site specific assessment of a GDF concurs with these results, that would provide a strong indication that the GDF is situated at suitable depth, in suitable geology and with sufficient engineered barriers to contain and isolate HAW as expected. Complex risk assessments should be conducted and included as part of NWS' safety submissions to regulators, who will judge, based on the evidence presented, whether there is a compelling case for the GDF presenting low risks to current and future generations.

A further indicative study showed the peak annual risk associated with a GDF at the same depth located in a higher strength rock (HSR) to be an order of magnitude larger than in an LSSR (1.87×10^{-7}.yr^{-1}), though still below the risk guidance level. UK policy seeks not to exclude any of the generic geological settings being considered, relying on voluntarism from willing communities as opposed to a "best geology" approach which would be difficult to implement. Therefore, whilst the geology won't be the single deciding factor in the siting decisions made, it will influence the site design, engineered barrier material choices and expectations by the GDF safety case. To ensure appropriate decisions are made in these areas, it's critical the UK continue to collaborate with other, more advanced national programmes and international disposal initiatives. This will enable NWS to better understand the behaviour of proposed materials that are as analogous to those proposed for the UK GDF, by harvesting and utilise data which can improve the efficacy of it's own, site specific models. This would allow for comparisons to be drawn between multiple sites in the UK, particularly those in different geological settings, if NWS are fortunate enough to have multiple consenting communities, and

aid site selection decision making.

It is recommended that further work should be done to model more complexly the effect of these sensitivities, the variability in performance expectations between geological disposal in LSSR and HSR environments, and to better establish a legitimate baseline against which GDF performance can more reliably be assessed.

10.2 Regulation Issues

10.2.1 International Experience

In Chapter 6, the regulation of geological disposal facilities in seven other countries (Finland, Sweden, France, Germany, Switzerland, Japan and USA), at varying stages in the development of their own disposal facilities for HAW and/or SNF was outlined. Commonalities were drawn from the collection of frameworks analysed, which could be used to measure the UK's regulatory framework against.

For example, each programme utilises a form of licensing or permissioning of radioactive waste and/or spent nuclear fuel disposal facilities, with a clear focus on public and environmental safety. In many cases, a staged approach to licensing was utilised, with hold points in a single licensing process, or requiring multiple licenses throughout the GDF lifecycle (e.g. licences for geological investigation, construction, operation etc.). This is not unlike the staged permissioning implemented through conditions attached to UK nuclear site licences, and does not indicate a change in approach is required for the UK's licensing of the GDF.

The enforcement of these licensing regimes often resembled a goal-setting approach, whereby the licensee is provided with guidance, safety goals or criteria which it is tasked with meeting by whichever means it deems appropriate. This is consistent with the approach the UK has taken to the regulation of nuclear installations to date and is just as relevant to that of the GDF.

A requirement of the Joint Convention, in each of the seven cases an independent regulator(s) is involved in the licensing process, though mostly on an advisory basis to licensees and decision makers (i.e. do not hold responsibility for issuing of nuclear site licences). Regulatory independence imparts a sense of integrity and impartiality in the enforcement of regulations, echoed by ONR in the UK. The US and Japanese programmes operate similarly to the UK, in that an independent regulator is responsible for the granting of nuclear licenses on regulated sites, with Government departments responsible for licensing decisions in other nations. Though it might lead one to question why the majority favour an approach different to the UK, there are a number of factors that might have led to the regulators in these nations not being involved in making such decisions, though primarily this stems from differences in the legal systems of each of these nations. As such I do not believe it should impact on the ONR's jurisdiction over licensing decisions in the UK, particularly given the UK's track record for successful licensing to date.

The designation of responsibility and liability in the interests of maintaining safety was another common feature identified in the national programmes assessed. In each case it is in fact the licensee/permissions holder who is deemed responsible for the upkeep of safety on the license site. The UK, as a signatory of the Paris and Brussels conventions, make licence holders liable for maintenance of safety and requires they hold sufficient insurance to ensure mitigation or restitution following safety related incidents. Provided the GDF is covered by the conventions, NWS will be subject to the UK Government's rates for third party liability.

Another key common aspect of the national programmes studied was mandatory consultation with interested parties in the vicinity of the proposed facility. Regulators often enforce this by placing requirements on prospective licensees as part of the licence application process. In the UK, regulators are required to consult under land-use planning laws for NSIPs (of which the GDF is one) and environmental permitting laws, and the siting process implemented by NWS is based on community engagement and voluntarism. As this is where previous attempts to implement geological disposal have previously failed, it is fair to conclude that NWS' prioritisation of

public acceptance in the siting process, including its many consultative activities, is sensible, proportionate and in-line with international practices.

Evidently the way the UK regulatory framework for nuclear safety is set up echoes many of the commonalities identified through the analysis of other national programmes. Minor variances were detected, for example in the inclusion of Environmental Impact Assessments (EIA) in the licensing application process of many programmes, though this can be attributed to the differing roles of the relevant regulators (and environmental court in the case of Sweden) in the licensing process for those nations.

10.2.2 UK Regulation of Nuclear Installations

The purpose of Chapter 7 was to map out the existing legal and regulatory framework as applied to nuclear installations in the UK, which governs the regulation of nuclear safety, environmental protection, security, nuclear safeguards and land-use planning. It was important to set out, prior to the proposal of a framework for the regulation of nuclear safety regulation at the GDF, the approach taken by regulators in their oversight of regulated facilities. This approach is somewhat unique to the UK, in that dual permissioning is implemented across its nuclear sites. ONR are responsible for regulating the licensing process for prescribed nuclear installations, and the relevant environment agency (Environment Agency, Natural Resource Wales, Scottish Environmental Protection Agency) responsible for implementing environmental permitting on nuclear sites. In each case, the dutyholder is required to produce safety submissions to justify and substantiate arguments related to nuclear safety and environmental protection, which permissions and continued development will depend upon. ONR's remit is broad, including the oversight of safety, security and safeguards, and unlike many other national programmes (analysed in Chapter 6), this extends to the granting of nuclear site licenses under the NIA.

The GDF will be licensed, permitted and subject to the same security and safeguards considerations as any other licensed UK NI. The existing approach provides stakeholders (e.g. members of

the public, politicians etc) with confidence in the regulators ability to assess the licensee's arrangements for the maintenance of safety on the licensed site. However this does limit the scope for change in any proposal of the future regulatory framework for nuclear safety. As the GDF represents a mixture of unique safety issues and a reduced hazard potential (relative to some NIs), it's important that it is regulated proportionately, without undue burden on the dutyholder for the GDF (NWS) or regulators (ONR/REA). Therefore applicability and proportionality are the biggest points of issue in proposing how nuclear safety regulation should be reflected in the framework applied to the GDF.

The mapping exercise described in Chapter 7 formed the basis for an analysis conducted in Chapter 8, which aimed to assess the applicability of the legal and regulatory framework when applied specifically to a geological disposal facility.

The opinions of representatives from a number of stakeholders in the GDF's development was sought on issues related to the nuclear site licensing and how its applicability to the GDF. The majority agreed that the way in which licensing is currently implemented would be easily transferable for the regulation of geological disposal, provided sufficient care and attention are taken to address GDF-specific issues, such as the representation of the underground facilities in 3-dimensions, flexibility to allow for the future disposal of SNF and exotic materials and the level of regulatory oversight afforded to underground areas of the site.

Many indicated that they believed the way in which the regulators for safety, security, safeguards and environmental protection integrated regulatory activities was adequate, but should be managed carefully to avoid duplicate requirements being placed on the licensee. In particular, given the GDF is a unique nuclear installation for the UK (i.e. unlike any licensed site to date), an efficient framework for regulation will be key to maintaining public and political confidence in the ability of the regulators to provide competent oversight of licensee's safety arrangements throughout the GDF lifecycle. The case was also put forward that a single regulator approach to regulation of the UK's NIs would improve the efficacy of the existing regulatory framework. Respondents did not identify any issues related to the regulation of environmental protection

or security on the GDF site, though it was highlighted that the GDF is likely to have to manage both safeguarded and non-safeguarded wastes, and that diversion scenarios may exist due to concurrent construction and operation of the GDF site. From analysis conducted on the safeguards framework, it was concluded that these issues do not require amendment to the legislative or regulatory requirements in order to be applied to the GDF.

The frameworks for the regulation of safety, environmental protection, security and nuclear safeguarding were examined through Chapter 8, in order to identify to what extent each is tailored to the requirements for geological disposal. It was found that whilst the GDF is eligible under the Nuclear Installations Act 1965 to be prescribed as an installation requiring a nuclear site licence, the regulations which prescribe licensable facilities, the Nuclear Installations Regulations 1971 (NIR71), do not include facilities for the disposal of radioactive waste and/or spent nuclear fuel within their remit. To conclude, for NWS to be able to obtain a nuclear site licence for the GDF, it's clear amendments should be made to UK legislation, with the NIR71 best placed to accomodate the necessary changes.

A review of the 36 standard conditions attached to nuclear site licenses was conducted to identify where any, changes or addition may be required when licensing the GDF. When considering the hazard potential and unique aspects of implementing geological disposal, it was concluded that there was a case for all 36 conditions to be applied to the license for the GDF, provided they are applied proportionately. It was identified that there could be scope for minor amendments to a couple of conditions to provide clarity on their applicability to geological disposal. These included, LC1 "Interpretation", which at present does not provide or include the term "disposal" in the definitions contained, whilst for LC2 "Marking the site boundary", a case could also be made for amendment or disapplication of part of the LC to enable clearer representation the underground site boundary. As part of the proposed regulatory framework produced in Chapter 9, additions to these conditions have been recommended, in order to seek clarity and broaden the inclusivity of the NSL to be applicable to the GDF. Ultimately, disapplication of LC2(4) in underground areas on the GDF site would preclude the need for amendment to LC2 whilst

ensuring the licensee does not fall foul of requirements for marking the underground boundary.

Upon review of the relevant legislation and licence conditions that the issue of waste retrievability, present in many international programmes, is not reflected in the UK licensing framework at present. It may be that a licensee can address this in its waste management arrangements, though nowhere is there a statutory obligation to consider retrievability of waste which has been disposed of. The NPS on geological disposal infrastructure acknowledges retrievability could be plausible if there were a compelling case during the operational phase of the GDF's lifecycle, and that this would become more difficult with time, and UK policy will dictate whether retrievability should be a consideration after a certain period of time. It was concluded that if this were to be brought into the regulatory framework, that an additional licence condition could be utilised to enforce it. Such a licence condition would require an environmental permit for the authorisation of disposal. The technical complexity and cost associated with the retrieval of disposed HAW may dissuade policymakers from making a statutory period of retrievability, and this is an issue I would recommend is investigated in more depth by the regulators and NWS.

It was concluded that there is very little need identified for changes to the legislation or regulations for environmental protection when applied to the GDF, on account of disposal already being considered in the relevant regulatory requirements. The environmental permitting regime has been tailored to a number of facilities, including those for the disposal of radioactive materials, and should not need to be amended to suitably and proportionately meet the needs of the GDF. A review of the generic conditions to be attached to environmental permits for radioactive waste disposal activities, and of the permit granted to the Low Level Waste Repository (LLWR), identified no reason for specific change. However, it is notable that many of the requirements of the environmental permit conditions come close to mirroring the requirements of the nuclear site licensing process e.g. in the production of a waste management and decommissioning plans under environmental permitting and the similarity to the terms of LC32, LC33 and LC35 of the nuclear site licence. This highlighted a potential for overlap in regulation, which should be managed carefully between regulators and the licensee to mitigate potential consequences

for the licensee. It was also noted that conditions related to the visual inspection of waste received on site and waste acceptance procedures, were present in the permit for LLWR, the closest analogue to the GDF in the UK. Visual inspection in this sense pertained to uncontained wastes arriving on site, and all HAW received on the GDF site will have already had to meet stringent transport regulations and waste acceptance criteria (WAC), as such it will not be necessary to provide this type of condition on the GDF's environmental permit. However the Guidance on Requirements for Authorisation (GRA) has not been updated since 2009, with the GRA linked to a previous siting policy and legislation no longer enforced in England and Wales for the protection of the environment. In order to best inform NWS and regulators on how best to comply, or assess compliance, with regulatory requirements for the authorisation of disposal, it will be necessary that the GRA be updated to reflect current legislation under which regulation is enforced and the existing siting policy in the UK. It would also be wise to utilise any information gained or lessons learned in the development of the GRR when reviewing and updating the GRA.

Analysis of the legal and regulatory framework for nuclear security, highlighted few areas for amendment in application to the GDF. What was apparent however is that some degree of ambiguity lies in the definitions of "nuclear premises" and "nuclear materials", which will require minor additions or actions in order to fully apply the GDF. It was highlighted that radioactive waste disposal facilities are not currently prescribed under the NISR as nuclear premises, but those for the storage of nuclear materials are, creating potential confusion over where on the GDF site the NISR are enforceable. As such I would advise that the NISR be amended to either include waste for disposal as waste "stored", or prescribe waste for disposal in its own right. It is the ONR's intention for the GDF to be regulated as a nuclear premises, as such it's logical to provide clarity on this matter. Regulatory changes should not be required however in ensuring HAW stored and disposed of on the GDF licensed site is covered by the NISR. Though HAW may not be explicitly be prescribed under the NISR as nuclear material covered by the regulations, the relevant Secretary of State has the ability to prescribe any materials he deems appropriate in the interests of nuclear security, meaning this approach should be ample

in ensuring all waste received on the GDF site is appropriately regulated.

Analysis of the UK's voluntary safeguards requirements found the current safeguards regime to be applicable to the GDF in its present form for the disposal of safeguarded materials. This conclusion is in agreement with the position of the IAEA on the implications on safeguards of geological disposal. However the congruent disposal of safeguarded and non-safeguarded materials may require a unique take from a regulatory perspective, compared to other national disposal programmes. Tailored monitoring, administrative or operational approaches will therefore be required to ensure that safeguards practices are sufficiently robust such that information related to non-safeguarded waste is not inadvertently communicated to the IAEA. This is an area in which regulators and the Ministry of Defence (as consignor of non-safeguarded waste) should focus in order to maintain national security.

10.2.3 Regulator Options

A brief analysis of the benefits and drawbacks of employing a joint regulatory regime versus a single regulator for the GDF was reported in Chapter 8. It was identified that there are multiple potential issues in the joint regulation of a facility, mainly related to areas of mutual and conflicting interests and the coordination of regulatory activities to avoid duplicate regulatory requirements. The implementation of a single regulator would enable an integrated approach which would ensure such challenges may be avoided, however it brings with it logistical challenges, particularly around the absorption of one regulator by another, and what impact this might have on devolved administrations. As such, it was concluded that the Memorandum of Understanding, under which the regulators currently operate, should suffice in meeting and addressing the challenges associated with joint regulation provided it is implemented appropriately and evolves with the GDF lifecycle. On this basis the GDF alone does not make a compelling enough case to drive a change at present.

As part of the proposed regulatory framework in Chapter 9, it was therefore recommended that

the primary regulators, the ONR and relevant environment agency, update and adhere to a Memorandum of Understanding which clearly establishes their regulatory roles, requirements and activities. This would be much more efficient in terms of time, cost and resource required for the formation single regulator. The regulators, through the MoU process, should focus future efforts on what aspects of alignment are most important to ensuring effective joint regulation of the GDF, and what updates to the MoU would look like to accommodate these.

More generally however, with the ONR regulating security, safeguards and safety on nuclear sites, it might be interesting for future researchers to investigate the viability and benefits of an integrated system for the regulation areas.

10.2.4 Proposed Approach

The primary conclusion drawn from the analysis presented in Chapter 8 was that only minor amendments to legislation or regulations will be required in order to appropriately apply the existing regulatory framework for nuclear safety, security, safeguards and environmental protection to the GDF. As such, the crux of the regulatory framework proposed in Chapter 9 was to reflect the proposed or required changes in order to ensure the GDF and the waste to be disposed of is covered by existing regulation.

Environmental Regulation

As the regulatory framework for environmental protection is already tailored to the permitting of facilities for the disposal of radioactive waste, no amendments to overarching legislation or regulations was proposed as discussed in Chapter 9. As shown however, it was proposed that the GRA be updated to reflect the environmental permitting regime and it's relationship to the most current legislation for those countries which no longer permit under the RSA 93. The Guidance on the Requirements for Release from Radioactive Substances Regulation 2018 (GRR) was identified as a model document to which the GRA should be aligned, and in which reference to authorisation under the Environmental Permitting Regulations 2016 should replace the RSA

93 for facilities in England and Wales. It's also therefore advised that the requirements of the GRA are updated, for example requirement 1 specifies the developer should follow a process by agreement for the development of a disposal facility, however this is no longer relevant for facilities regulated under the EPR 16 to which a staged regulatory approach will be taken.

Nuclear Safety and Site Licensing

Regards nuclear safety, disposal facilities are prescribable under the Nuclear Installations Act 1965 (NIA65), but not prescribed under the Nuclear Installations Regulation (NIR71). As such, amendments were proposed to the NIA65 and NIA71, which would individually meet the requirement for the GDF to be licensed under the NIA. It was acknowledged that any change to the NIA, would require primary legislation to be passed through Parliament, which could be more time and resource intensive than making an addition to the NIR71. Therefore inclusion of a facility for the disposal of SNF, HAW and long-lived LLW unsuitable for disposal by other means, in the list of prescribed facilities contained in the NIR71 was identified as a favourable option through which this could be achieved.

A number of principles based on international best practice were identified against which the regulatory framework for nuclear safety on the GDF site should be assessed. The UK's nuclear site licensing regime was measured against these principles, which included a clear and predictable regulatory process, independent regulation and appropriate enforcement powers for regulators, to reinforce why the regime should be applied in its existing form to the GDF. It's evident that the present approach is, barring the minor amendments set out in the proposed regulatory framework, appropriately set out and flexible to meet the requirements of the principles when specifically applied to the GDF.

As analysis of the 36 standard licence conditions identified each to be suitable and applicable to the GDF, it was proposed they be attached, primarily in their existing form, to the nuclear site licence for the GDF. As it was identified there might be scope for LC1 and LC2 to be worded in a way more inclusive to facilities for disposal, small additions have been proposed.

For LC1 "Interpretation", two options for amendment were proposed to make for the inclusion of disposal. A specific definition for "disposal" of waste in conventional landfill, near-surface or geological disposal facilities, or the inclusion of "disposal" within the definition of "operations" were identified as ways in which disposal could be specifically defined or addressed in the interpretation of the licence conditions. Based upon these, it would be recommended, to avoid having to define or make reference to waste classifications or to specific methods of disposal, appropriate for a set of standard conditions, that disposal be included in the definition of operations already contained in LC1.

If it became UK policy to include waste retrievability in the management requirements for the GDF, there's scope for its inclusion in the licensing or environmental permitting processes. Though there remains debate as to the necessity for and impact of the inclusion of retrievability in the regulations, a new licence condition, LC37 "Retrieval of radioactive waste" was proposed to provide for the retrieval of radioactive waste for a period specified by the ONR, as a means of addressing this potential future issue.

The suitability of a condition such as this should form the basis for further work, to understand whether the level of risk associated with retrievability is significant, and whether a condition such as that proposed is something the ONR could lawfully look to attach at when not necessarily aimed at safety, security or safeguards requirements. This research, conducted by or in conjunction with the UK Government, would ensure that a sound policy decision can be made on waste retrievability for the GDF, and based upon this, how it can best be reflected in the legal framework or regulatory tools available to the regulators.

Security and Nuclear Safeguards

It was identified in Chapter 8 that the Nuclear Installations Security Regulations (NISR) is ambiguous in its definitions of nuclear premises and nuclear material for the purpose of regulating the security for the GDF, despite the ONR's position on the regulation of the GDF under the NISR. As such, proposals to add to the definition of nuclear premises was proposed to

ensure that disposal was sufficiently referenced, meaning that both the storage and disposal facilities on site can be unequivocally covered by the NISR. Given the powers ascribed to the Secretary of State to prescribe nuclear materials under the NISR, it is not necessary that specific amendments be made to the schedule under Regulations 3(3) and 3(4) for the inclusion of HAW. In order to address the issue of whether HAW was declared as nuclear material under regulation 3 of the NISR, it was also proposed that work be conducted to determine whether HAW should be prescribed specifically as a nuclear material to which the regulations may be applied, or whether they should be included within the definition of another Category I/II or III material under the NISR.

No specific recommendations were proposed in Chapter 9 for adaptation of the current framework for the implementation of safeguards provisions on the GDF site. Based upon stakeholder opinions obtained in Chapter 8, that the arrangements made between the licensee (NWS), regulator (ONR) and the IAEA might need to specifically address the co-disposal of safeguarded and non-safeguarded materials, as well as the congruent construction and operation of the GDF facility, which might take the form of increased provisions for monitoring, particularly in underground areas.

10.3 Recommendations for Further Research

The geological disposal facility will be a complex, unique facility for the UK. As portrayed throughout this thesis, it will come with a variety of unique safety and regulatory challenges. It is anticipated that the low radiological risk to the public both now and in the future, posed by the GDF will be lower than recommended guidance levels deemed tolerable by regulators. Many factors including the geological setting, it's depth, the engineered barrier materials employed and the inventory of waste ultimately disposed of in the GDF will impact on the safety arguments that underpin the safety case submissions made by NWS throughout the GDF's lifecycle, which the regulators will assess before considering granting the relevant permissions to proceed with

its development. Based on the work conducted throughout this project, it is recommended that areas of focus for future work should include:

- further modelling which considers a biosphere that is primarily inshore (i.e. within 12 nautical miles of the coastline) and its impact on the radiological risk to the public, both now and in the future;
- gaining a better understanding of the specific site, through complex total system modelling, intrusive site investigation and experimentation (once a site for the GDF has been selected);
- innovation in the development and selection of appropriate EBS materials, tailored to the GDF site selected;
- the affect of local (GDF/geology) conditions on the efficacy of engineered barrier materials, and the potential impact on the co-location of multiple waste streams in a single repository;
- the impact of future policy decisions on the inventory for disposal in the GDF and its influence on site suitability and GDF design;
- the necessity for one, or multiple GDF sites based upon future projections and policy decisions around the use of nuclear energy in the UK;
- understanding the risks associated with waste retrievability, whether retrievability is legally enforceable and where it would be most appropriate to include retrievability in a future regulatory framework;
- the implications of hosting safeguarded and non-safeguarded materials on the implementation of safeguards regulation, and novel solutions to tackling potential issues;
- maintaining and improving local stakeholder involvement beyond the established site selection process.

In principle, a GDF should be capable of safely containing and isolating the UK's HAW for at least tens or hundreds of thousands of years. Natural analogues, international studies and the

advanced nature of national programmes across the world are all testament to this. Once a site is selected and a deeper understanding of the local environment has been established, NWS should be able to establish with a higher degree of confidence how the UK's GDF will perform. This may be some years away, but the regulatory framework is evidently set up to accommodate the majority of the unique aspects and challenges associated with geological disposal. Many facets of the regulatory framework for nuclear safety, environmental protection, security and safeguards of UK nuclear installations are sufficiently flexible and robust, that it leaves little doubt that with a few minor changes, the GDF can be regulated within the existing nuclear regulatory framework in a way that is proportionate to the hazard potential posed by the final disposal of the UK's legacy and future higher activity waste.

Though the question still remains- just because a more than suitable framework for regulating the GDF exists, could it be done better? Or differently? As touched upon in Chapters 8 and 9, an integrated regulator may bring about certain efficiencies in the regulation and inspection of the GDF throughout its lifecycle. Alternatively a single process for obtaining a licensing/permitting instrument, which covers nuclear safety and environmental protection, and which also draws in nuclear security and safeguards requirements (particularly as these are both already within the remit of the nuclear safety regulator) would be logical if we were able and willing to start again. To my mind this would provide confidence that regulatory standards are consistent across all facets of regulation, including those which are voluntary (i.e. nuclear safeguards). A GDF will be a highly complex infrastructure project, one that only becomes more complex as NWS makes its way through the different stages of its lifecycle; as such, any means of simplification without compromising on quality would seem a good idea. Though it may be too late for the UK to ponder such scenarios, those nations with less mature GDF programmes might benefit from the hindsight they're afforded when looking at implementing geological disposal in the decades that follow the examples of Finland, Sweden, and in the not too distant future, the UK.

Bibliography

[1] UK Parliament, "Energy Act, 1946 (1946 Chapter 80)," Tech. Rep., 1946. [Online]. Available: https://www.legislation.gov.uk/ukpga/Geo6/9-10/80.

[2] HM Government, "Net Zero Strategy: Build Back Greener," Tech. Rep., 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf.

[3] UK Parliament, *Radioactive Substances Act 1993 (1993 Chapter 12)*, 1993. [Online]. Available: https://www.legislation.gov.uk/ukpga/1993/12/pdfs/ukpga_19930012_en.pdf.

[4] ——, *Environmental Permitting (England and Wales) Regulations 2016 (SI no. 2016/1154)*, 2016. [Online]. Available: https://www.legislation.gov.uk/uksi/2016/1154/made.

[5] Nuclear Decommissioning Authority, "2019 UK Radioactive Waste Detailed Data," Department for Business, Energy & Industrial Strategy and Nuclear Decommissioning Authority, London, Tech. Rep., 2019. [Online]. Available: https://ukinventory.nda.gov.uk/?action=export_pdf&tid=90299adf9b76a9c0d448a1bbc39b1b6f&display_format=100&summary=Showing%20all%20unfiltered%20results..

[6] ——, "2019 UK Radioactive Waste Inventory," Department for Business, Energy & Industrial Strategy and the Nuclear Decommissioning Authority, NDA & BEIS, London, UK, Tech. Rep., 2019, pp. 1–70. [Online]. Available: https://ukinventory.

nda.gov.uk/?action=export_pdf&tid=90299adf9b76a9c0d448a1bbc39b1b6f&display_format=100&summary=Showing%20all%20unfiltered%20results..

[7] ——, "Integrated Waste Management- NDA Higher Activity Waste Strategy," National Decommissioning Authority, NDA, UK, Tech. Rep. May, 2016, p. 4. [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/522435/NDA_Higher_Activity_Waste_Strategy_2016.pdf.

[8] Posiva Oy, *Excavation of world's first final deposition tunnels starts in Posiva's ONKALO facility*, 2021. [Online]. Available: https://www.posiva.fi/en/index/news/pressreleasesstockexchangereleases/2021/excavationofworldsfirstfinaldeposit
html.

[9] Radioactive Waste Management Ltd., *RWM welcomes formation of Theddlethorpe GDF Working Group*, 2021. [Online]. Available: https://www.gov.uk/government/news/rwm-welcomes-formation-of-theddlethorpe-gdf-working-group.

[10] ——, *RWM welcomes proposal for GDF Community Partnerships in Copeland*, 2021. [Online]. Available: https://www.gov.uk/government/news/rwm-welcomes-proposal-for-gdf-community-partnerships-in-copeland.

[11] ——, *RWM welcomes proposed GDF search area in Allerdale*, 2021. [Online]. Available: https://www.gov.uk/government/news/rwm-welcomes-proposed-gdf-search-area-in-allerdale.

[12] UK Parliament, *Nuclear Installations Act 1965 (1965 Chapter 57)*, 1965. [Online]. Available: https://www.legislation.gov.uk/ukpga/1965/57/contents.

[13] Office for Nuclear Regulation, "Licensing Nuclear Installations," Tech. Rep. January, 2019. [Online]. Available: https://www.onr.org.uk/licensing-nuclear-installations.pdf.

[14] HM Government, "The Energy White Paper - Powering our Net Zero Future," Tech. Rep. December, 2020, pp. 903–905. [Online]. Available: http://www.ret.gov.au/energy/facts/white_paper/Pages/energy_white_paper.aspx.

[15] Nuclear Decommissioning Authority, "Radioactive Wastes in the UK: Context and Methodology Report," Tech. Rep., 2017. [Online]. Available: https://ukinventory.nda.gov.uk/wp-content/uploads/sites/18/2014/01/2016UKRWMI-Context-and-methodology.pdf.

[16] Committee on Radioactive Waste Management, "Managing our Radioactive Waste Safely: CoRWM's recommendations to Government (CoRWM Doc 700)," CoRWM, London, London, Tech. Rep. CoRWM Doc 700, 2006, p. 195. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/294118/700_-_CoRWM_July_2006_Recommendations_to_Government_pdf.pdf.

[17] G. MacKerron, "Evaluation of nuclear decommissioning and waste management," University of Sussex, Sussex, UK, Tech. Rep., 2012, pp. 1–129. [Online]. Available: https://core.ac.uk/download/pdf/111605945.pdf%20http://sro.sussex.ac.uk/40037/.

[18] International Atomic Energy Agency, "IAEA Safety Standards for protecting people and the environment: Geological Disposal Facilities for Radioactive Waste for protecting people and the environment No. SSG-14 Specific Safety Guide," IAEA, Vienna, Tech. Rep., 2011. [Online]. Available: http://www-ns.iaea.org/standards/.

[19] Department for Business Energy & Industrial Strategy, "Implementing Geological Disposal-Working With Communities: An updated framework for the long-term management of higher activity radioactive waste," BEIS, London, UK, Tech. Rep., 2018. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/766643/Implementing_Geological_Disposal_-_Working_with_Communities.pdf.

[20] Low Level Waste Repository Ltd, "International Approaches to Radioactive Waste Classification National Waste Programme O LLW Repository Ltd Acknowledgements," LLWR Ltd, Tech. Rep., 2016, p. 24. [Online]. Available: http://llwrsite.com/wp-

content/uploads/2016/11/NWP-REP-134-International-Approaches-to-RW-Classification-Oct-2016.pdf.

[21] Radioactive Waste Management Ltd., "Inventory for geological disposal- Main Report," RWM Ltd., Tech. Rep., 2018. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/835814/Inventory_for_geological_disposal_a.pdf.

[22] International Atomic Energy Agency, "Classification of Radioactive Waste (General Safety Guide No. GSG-1)," IAEA, Vienna, Tech. Rep., 2009, pp. 14–15. [Online]. Available: http://www-pub.iaea.org/MTCD/publications/PDF/Pub1419_web.pdf.

[23] Nuclear Decommissioning Authority, "Radioactive Wastes in the UK: A Summary of the 2016 Inventory," NDA, Tech. Rep., 2017. [Online]. Available: https://ukinventory.nda.gov.uk/wp-content/uploads/sites/18/2017/03/High-Level-Summary-UK-Radwaste-Inventory-2016.pdf.

[24] Great Britain. Radioactive Waste Management Advisory Committee., "Radioactive Waste Management Advisory Committee : eleventh annual report," Tech. Rep., 1990, p. 126. [Online]. Available: https://inis.iaea.org/search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=22026657.

[25] Nuclear Decommissioning Authority & Sellafield Ltd, *Operations to end at Sellafield's Magnox Reprocessing Plant*, 2022. [Online]. Available: https://www.gov.uk/government/news/operations-to-end-at-sellafields-magnox-reprocessing-plant.

[26] Nuclear Decommissioning Authority, "2013 UK Radioactive Waste Inventory: Radioactive Waste Composition," Tech. Rep., 2014. [Online]. Available: https://ukinventory.nda.gov.uk/wp-content/uploads/sites/18/2014/02/14D040_NDASTSTY140011_-_Radioactive_Waste_Composition.pdf.

[27] M. T. Harrison, "Vitrification of High Level Waste in the UK," *Procedia Materials Science*, vol. 7, pp. 10–15, 2014, ISSN: 2211-8128. DOI: 10.1016/J.MSPRO.2014.10.003.

[Online]. Available: https://www.sciencedirect.com/science/article/pii/S2211812814010463.

[28] Department for Environment Food & Rural Affairs, "Policy for the Long Term Management of Solid Low Level Radioactive Waste in the United Kingdom DTI and the Devolved Administrations," DEFRA, London, UK, Tech. Rep., 2007, p. 5. [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/254393/Low_level_waste_policy.pdf.

[29] Nuclear Decommissioning Authority, "Wet ILW at Hinkley- (Conceptual stage) Summary of Assessment Report," NDA RWMD, UK, Tech. Rep., 2008, pp. 1–5. [Online]. Available: https://rwm.nda.gov.uk/publication/executive-summary-letter-of-compliance-assessment-report-packaging-of-hinkley-wet-intermediate-level-waste-ilw-may-2008/?download.

[30] ——, "Radioactive Wastes in the UK: UK Radioactive Waste Inventory Report," NDA, Tech. Rep., 2017, pp. 1–205. [Online]. Available: https://ukinventory.nda.gov.uk/wp-content/uploads/sites/18/2014/01/2016UKRWMI-UK-Radioactive-waste-inventory-report.pdf.

[31] Low Level Waste Repository Ltd, "Waste Acceptance Criteria-Low Level Waste Disposal (WSC-WAC-LOW – Version 5.0)," LLWR Ltd, Tech. Rep., 2016. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/690797/Waste_Acceptance_Criteria_-_Low_Level_Waste_WSC-WAC-LOW-Version-5.pdf.

[32] International Atomic Energy Agency, "Terminology Used in Nuclear Safety and Radiation Protection 2018 Edition," *IAEA Safety Glossary*, p. 238, 2019. [Online]. Available: http://www-pub.iaea.org/MTCD/Publications/PDF/PUB1830_web.pdf.

[33] Nuclear Decommissioning Authority, "Radioactive Wastes in the UK: Radioactive Wastes and Materials not Reported in the 2016 Waste Inventory," Tech. Rep., 2017. [Online]. Available: https://ukinventory.nda.gov.uk/wp-content/uploads/

sites/18/2014/01/2016UKRWMI-Radioactive-wastes-and-materials-not-reported-in-2016-UK-inve....pdf.

[34] B. F. Dunnett, "Review of the Development of UK High Level Waste Vitrified Product (Nexia Solutions (06) 7926)," Nirex, NDA, Prepared by Nexia Solutions for NDA, UK, Tech. Rep. 4, 2007, pp. 11–17. [Online]. Available: https://rwm.nda.gov.uk/publication/review-of-the-development-of-uk-high-level-waste-vitrified-product/.

[35] S. K. Johal, C. Boxall, C. Gregson, and C. J. Steele, "Ruthenium Volatilisation from Reprocessed Spent Nuclear Fuel-Studying the Baseline Thermodynamics of Ru(III)," Tech. Rep., 2015. [Online]. Available: http://eprints.lancs.ac.uk/78523/2/SJohal_CBoxall_ECSTrans_Paper_16_July_2015_Final_v2.pdf.

[36] G. F. Sinclair, "Encapsulation of ILW Raffinate in the Dounreay Cementation Plant," in *2nd International Topical Meeting on Research Reactor Fuel Management*, 1998, pp. 205–209. [Online]. Available: https://inis.iaea.org/collection/NCLCollectionStore/_Public/32/030/32030503.pdf.

[37] Nuclear Decommissioning Authority, "DFR Raffinate at Dounreay (Interim stage)," NDA RWMD, UK, Tech. Rep. April 2008, 2006, pp. 1–4. [Online]. Available: https://rwm.nda.gov.uk/publication/executive-summary-letter-of-compliance-assessment-report-dounreay-fast-reactor-dfr-raffinate-april-2008/?download.

[38] ——, "Sellafield Wastes Encapsulation Plant (Periodic Review) Summary of Assessment Report," Tech. Rep. April, 2008. [Online]. Available: https://rwm.nda.gov.uk/publication/summary-of-assessment-for-sellafield-wastes-encapsulation-plant-letter-of-compliance-periodic-review/?download.

[39] Radioactive Waste Management Ltd., "Waste Package Specification and Guidance Documentation: Specification for Waste Packages Containing Low Heat Generating Waste : Part D – Container Specific Requirements (WPS/300/04)," Tech. Rep.

June, 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/935713/WPS_300_04_Part_D_-_Specification_for_Waste_Packages_Containing_Low_Heat_Generating_Waste.pdf.

[40] ——, "Geological Disposal: Guidance on the use of organic polymers for the packaging of low heat generating wastes (WPSGD no. WPS/901/02)," Tech. Rep. April, 2015. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/876856/WPS901-02-Geological-Disposal-Guidance-on-the-use-of-organic-polymers-for-the-packaging-of-low-heat-generating-wastes.pdf.

[41] ——, "Geological Disposal: Waste Package Evolution Status Report (NDA Report no. DSSC/451/01)," NDA, NDA, UK, Tech. Rep., 2016. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-waste-package-evolution-status-report/.

[42] M. I. Ojovan and W. E. Lee, "Glassy Wasteforms for Nuclear Waste Immobilization," *Metallurgical and Materials Transactions A*, vol. 42, no. 4, pp. 837–851, 2011, ISSN: 1073-5623. DOI: 10.1007/s11661-010-0525-7. [Online]. Available: http://link.springer.com/10.1007/s11661-010-0525-7.

[43] W. Burns, A. Hughes, J. Marples, R. Nelson, and A. Stoneham, "Effects of radiation on the leach rates of vitrified radioactive waste," *Journal of Nuclear Materials*, vol. 107, no. 2-3, pp. 245–270, 1982, ISSN: 0022-3115. DOI: 10.1016/0022-3115(82)90424-X. [Online]. Available: https://www.sciencedirect.com/science/article/pii/002231158290424X.

[44] Radioactive Waste Management Ltd., "Geological Disposal: Generic Specification for waste packages containing high heat generating wastes (WPSGD no. WPS/240/01)," NDA, UK: NDA, Tech. Rep., 2016. [Online]. Available: https://rwm.nda.gov.uk/

publication/generic-specification-for-waste-packages-containing-hhgw-impacts-of-gd-concepts-on-packaging-criteria/.

[45] Nuclear Decommissioning Authority, *Vitrified High-Level Waste at Sellafield (Pre-Conceptual Stage) Summary of Assessment Report*, NDA RWMD, UK, 2009. [Online]. Available: https://rwm.nda.gov.uk/publication/executive-summary-letter-of-compliance-assessment-report-vitrified-high-level-waste-april-2009/?download.

[46] M. T. Harrison, "The Effect of Composition on Short- and Long-term Durability of UK HLW Glass," *Procedia Materials Science*, vol. 7, pp. 186–192, 2014, ISSN: 2211-8128. DOI: 10.1016/j.mspro.2014.10.025. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2211812814010682.

[47] ——, "Review of Glass Dissolution Rates for use in the Disposal System Safety Case Performance Assessment Models (NNL (10) 10734)," NNL Report: NNL (10) 10734, Prepared by NNL for NDA, UK, Tech. Rep. Volume 3, 2010. [Online]. Available: https://rwm.nda.gov.uk/publication/nnl_10_10734-review-of-glass-dissolution-rates-issue-3-final-for-bibliography/.

[48] C. L. Corkhill, N. J. Cassingham, P. G. Heath, and N. C. Hyatt, "Dissolution of UK High-Level Waste Glass Under Simulated Hyperalkaline Conditions of a Colocated Geological Disposal Facility," *International Journal of Applied Glass Science*, vol. 4, no. 4, pp. 341–356, 2013. DOI: 10.1111/ijag.12042. [Online]. Available: www.ceramics.org/IJAGS.

[49] Nuclear Decommissioning Authority, "Geological Disposal- Radionuclide behaviour status report (NDA Report no. NDA/RWMD/034)," Tech. Rep. NDA/RWMD/034, 2010, pp. 1–152. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-radionuclide-behaviour-status-report-december-2010/?download.

[50] Radioactive Waste Management Ltd., "Geological Disposal: Behaviour of Radionuclides and Non-radiological Species in the Groundwater Status Report (NDA Report no. DSSC/456/01)," NDA, UK, Tech. Rep. December, 2016. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/635258/NDA_Report_no_DSSC-456-01_-_Geological_Disposal_-_Behavior_of_Radionuclides_and_Non-radiological_Species_in_Groundwater_Status_Report.pdf.

[51] Nuclear Decommissioning Authority, "The 2010 UK Radioactive Waste Inventory: Main Report," NDA & BEIS, London, UK, Tech. Rep., 2011, pp. 1–131. [Online]. Available: http://www.nda.gov.uk/ukinventory/documents/Reports/upload/2010-UK-Radioactive-Waste-Inventory-Main-Report.pdf.

[52] ——, "The 2013 UK Radioactive Waste Inventory Waste Quantities from all Sources," NDA & BEIS, London, UK, Tech. Rep., 2014. [Online]. Available: https://ukinventory.nda.gov.uk/document/2013_waste_quantities_from_all_sources/.

[53] ——, *End in sight for reprocessing nuclear fuel at Sellafield*, 2017. [Online]. Available: https://nda.blog.gov.uk/2017/01/24/end-in-sight-for-reprocessing-nuclear-fuel-at-sellafield/.

[54] ——, "Progress on Plutonium Consolidation, Storage and Disposition," NDA, UK, Tech. Rep. March, 2019, pp. 1–14. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/791046/Progress_on_Plutonium.pdf.

[55] Sellafield Ltd, *Green light to restart Magnox Reprocessing*, 2020. [Online]. Available: https://www.gov.uk/government/news/green-light-to-restart-magnox-reprocessing.

[56] United Kingdom Nirex Limited, "Options for Radioactive Waste Management that have been Considered by Nirex," Tech. Rep. Nirex Report No: N/049, 2002, pp. 1–27. [Online]. Available: https://rwm.nda.gov.uk/publication/012-options-for-

radioactive-waste-management-that-have-been-considered-by-nirex-2002/?download#:~:text=The%20options%20described%20are%20sea,storage%2C%20and%20partitioning%20and%20transmutation.&text=Since%20it%20was%20created%20in,term%20management%20of%20radioactive%20waste..

[57] Department for Environment Food & Rural Affairs, "Managing Radioactive Waste Safely Proposals for developing a policy for managing solid radioactive waste in the UK," DEFRA, London, UK, Tech. Rep., 2001. [Online]. Available: www.defra.gov.uk/environment/index.htm.

[58] OSPAR Commission, "Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention)," 1992. [Online]. Available: https://www.ospar.org/site/assets/files/1290/ospar_convention-1.pdf.

[59] International Maritime Organisation, "Convention On The Prevention Of Marine Pollution By Dumping Of Wastes And Other Matter," Tech. Rep., 1972. [Online]. Available: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/LC1972.pdf.

[60] World Nuclear Association, *Storage and Disposal of Radioactive Waste*, 2021. [Online]. Available: https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/storage-and-disposal-of-radioactive-waste.aspx.

[61] French Parliament, "Act No 91-1381 of 30 December 1991 on research on radioactive waste management," 1991. [Online]. Available: https://inis.iaea.org/collection/NCLCollectionStore/_Public/24/030/24030782.pdf?r=1.

[62] Department for Environment Food & Rural Affairs, "Managing Radioactive Waste Safely : A Framework for Implementing Geological Disposal," DEFRA, London, UK, Tech. Rep., 2008, p. 94. [Online]. Available: https://www.gov.uk/government/publications/managing-radioactive-waste-safely-a-framework-for-implementing-geological-disposal.

[63] Nuclear Energy Agency, "Moving Forward With Geological Disposal of Radioactive Waste: an NEA RWMC Collective Statement," OECD, NEA/OECD, Paris, Tech. Rep. 6433, 2008, p. 12. [Online]. Available: https://www.oecd-nea.org/rwm/reports/2008/nea6433-statement.pdf%20papers2://publication/uuid/027D594F-130C-4733-9001-D39852F9E10F.

[64] International Atomic Energy Agency, "Geological Disposal Facilities for Radioactive Waste- Specific Safety guide (No. SSG-14)," IAEA, IAEA, Vienna, Tech. Rep., 2011, p. 1. [Online]. Available: http://www-ns.iaea.org/standards/.

[65] P. Sellin and O. X. Leupin, "The use of clay as an engineered barrier in Radioactive Waste Management - A review," *Clays and Clay Minerals*, vol. 61, no. 6, pp. 477–498, 2014, ISSN: 15528367. DOI: 10.1346/CCMN.2013.0610601.

[66] Environment Agency, "Regulating geological disposal: an overview," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/documents/2019/geological-disposal-overview.pdf.

[67] Her Majesty's Stationery Office, "Royal Commission On Environmental Pollution Sixth Report Nuclear Power And The Environment," Tech. Rep., 1976. [Online]. Available: http://webarchive.nationalarchives.gov.uk/20110322144120/http://www.rcep.org.uk/reports/06-nuclear/1976-06nuclear.pdf.

[68] J. Mather, D. Greenwood, and P. Greenwood, "Burying Britain's radioactive waste-the geological areas under investigation," *Nature*, vol. 281, pp. 332–334, 1979. [Online]. Available: https://www.nature.com/articles/281332a0.pdf.

[69] United Kingdom Nirex Limited, "TECHNICAL NOTE: Review of 1987-1991 Site Selection for an ILW/LLW Repository," Tech. Rep., 2005. [Online]. Available: https://www.davidsmythe.org/nuclear/nirex%202005%20review%20of%201987-91_site_selection.pdf.

[70] ——, "The Way Forward," United Kingdom Nirex Limited, Tech. Rep., 1987. [Online]. Available: https://www.geos.ed.ac.uk/homes/rsh/The_Way_Forward_United_Kingdom_Nirex_Limited_1987_-_colour.pdf.

[71] University of East Anglia and Environmental Risk Assessment Unit (ERAU), "Responses to The Way Forward," International Nuclear Information System, Tech. Rep., 1988, p. 52. [Online]. Available: https://inis.iaea.org/search/search.aspx?orig_q=RN:20042674.

[72] D. Gore, "The Underground Disposal of Radioactive Waste (Research paper 96/113)," 1996. [Online]. Available: http://researchbriefings.files.parliament.uk/documents/RP96-113/RP96-113.pdf.

[73] West Cumbria Managing Radioactive Waste Safely Partnership, "The Final Report of the West Cumbria Managing Radioactive Waste Safely Partnership," Copleand Borough Council, Tech. Rep., 2012. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=http%3A%2F%2Fwww.westcumbriamrws2013.info%2Fdocuments%2F307-Executive_Summary_of_the_West_Cumbria_MRWS_Partnership%27s_Final_Report_August_2012.pdf&clen=391870&chunk=true.

[74] Department of Energy & Climate Change, "Managing Radioactive Waste Safely: The Siting Process For A Geological Disposal Facility Consultation Response," DECC, Tech. Rep., 2013. [Online]. Available: http://councilportal.cumbria.gov.uk/documents/s24017/mrws%20Consultation%20FINAL.pdf.

[75] ——, "Implementing Geological Disposal: A Framework for the long-term management of higher activity radioactive waste," Department of Energy & Climate Change (DECC), DECC, London, UK., Tech. Rep. URN14D/235, 2014, pp. 5–54. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/332890/GDF_White_Paper_FINAL.pdf.

[76] Radioactive Waste Management Ltd., *RWM welcomes announcement of first 'Working Group'*, 2020. [Online]. Available: https://www.gov.uk/government/news/rwm-welcomes-announcement-of-first-working-group.

[77] ——, *RWM welcomes launch of second GDF 'Working Group'*, 2020. [Online]. Available: https://www.gov.uk/government/news/rwm-welcomes-launch-of-second-gdf-working-group.

[78] ——, *RWM welcomes Mid Copeland taking next step in GDF process*, 2021. [Online]. Available: https://www.gov.uk/government/news/rwm-welcomes-mid-copeland-taking-next-step-in-gdf-process.

[79] ——, *Second GDF Community Partnership forms in Cumbria*, 2021. [Online]. Available: https://www.gov.uk/government/news/second-gdf-community-partnership-forms-in-cumbria?utm_medium=email&utm_campaign=govuk-notifications&utm_source=59ebe669-1188-4127-8cdc-68fe9765312e&utm_content=daily.

[80] ——, *Allerdale GDF Community Partnership forms*, 2022. [Online]. Available: https://www.gov.uk/government/news/allerdale-gdf-community-partnership-forms.

[81] Euridice, *Geological Disposal in Clay*, 2016. [Online]. Available: https://www.euridice.be/en/content/geological-disposal-clay.

[82] Nuclear Waste Management Organisation, *Deep Geological Repository*, 2017. [Online]. Available: https://www.nwmo.ca/en/A-Safe-Approach/Facilities/Deep-Geological-Repository.

[83] J. Noronha, "Deep Geological Repository Conceptual Design Report Crystalline / Sedimentary Rock Environment," NWMO, Toronto, Canada, Tech. Rep., 2016. [Online]. Available: https://www.nwmo.ca/~/media/Site/Reports/2016/06/08/10/03/APM_REP_00440_0015_R001.ashx?la=en.

[84] J. Wang, L. Chen, R. Su, and X. Zhao, "The Beishan underground research laboratory for geological disposal of high-level radioactive waste in China: Planning, site selection, site characterization and in situ tests," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 10, no. 3, pp. 411–435, 2018, ISSN: 16747755. DOI: 10.1016/j.jrmge.2018.03.002. [Online]. Available: https://doi.org/10.1016/j.jrmge.2018.03.002.

[85] The Czech Radioactive Waste Repository Authority (SÚRAO), *DGR Design*, 2019. [Online]. Available: https://www.surao.cz/en/experts/dgr-design/.

[86] L'Agence nationale pour la gestion des déchets radioactifs (ANDRA), *Cigeo*, 2020. [Online]. Available: https://international.andra.fr/solutions-long-lived-waste/cigeo.

[87] Posiva Oy, *Geological final Disposal*, 2020. [Online]. Available: https://www.posiva.fi/en/index/finaldisposal/geologicalfinaldisposal.html#:~:text=Posiva%20has%20solved%20final%20disposal,Finland%20also%20in%20the%20future.&text=In%20Finland%2C%20final%20disposal%20means,the%20oldest%20in%20the%20world..

[88] Bundesgesellschaft für Endlagerung mbH (BGE), *Sub-areas Interim Report*, 2020. [Online]. Available: https://www.bge.de/en/sitesearch/sub-areas-interim-report/.

[89] The Nuclear Waste Organization of Japan (NUMO), *Japanese Geological Disposal Program*, 2019. [Online]. Available: https://www.numo.or.jp/en/jigyou/new_eng_tab01.html.

[90] Centrale Organisatie Voor Radioactief Afval (COVRA), *Deep Geological Disposal*, 2019. [Online]. Available: https://www.covra.nl/en/radioactive-waste/deep-geological-disposal/.

[91] Nuclear Decommissioning Authority, "Geological Disposal: How the world is dealing with its radioactive wastes," NDA, UK, Tech. Rep. July, 2013, pp. 1–8. [Online].

Available: https://rwm.nda.gov.uk/publication/how-the-world-is-dealing-with-its-radioactive-wastes/?download.

[92] Reuters, *South Korea to pick spent nuclear fuel site by 2028, eyes overseas storage*, 2016. [Online]. Available: South%20Korea%20to%20pick%20spent%20nuclear%20fuel%20site%20by%202028,%20eyes%20overseas%20storage.

[93] Svensk Kärnbränslehantering AB (SKB), "Long-term safety for the final repository for spent nuclear fuel at Forsmark," Swedish Nuclear FUel and Waste Management Co, Tech. Rep., 2011, pp. 1–341. [Online]. Available: http://www.skb.se/upload/publications/pdf/TR-11-01_vol3.pdf.

[94] ——, *The Spent Fuel Repository*, 2021. [Online]. Available: https://www.skb.com/future-projects/the-spent-fuel-repository/.

[95] National Cooperative for the Disposal of Radioactive Waste (NAGRA), *Deep geological repository: safe underground disposal of radioactive waste*, 2021. [Online]. Available: https://www.nagra.ch/en/deep-geological-repository.

[96] United Arab Emirates, "United Arab Emirates Third National Report On Compliance With The Obligations Of The Joint Convention On The Safety Of Spent Fuel Management And On The Safety Of Radioactive Waste Management," Tech. Rep., 2017. [Online]. Available: https://www.iaea.org/sites/default/files/national_report_of_the_united_arab_emirates_for_the_6th_review_meeting_-_english.pdf.

[97] Committee on Radioactive Waste Management, "CoRWM Position Paper: GDF Should only Target Best Geology," London, 2018. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/753945/3468_O_Best_Geology.pdf.

[98] Radioactive Waste Management Ltd., "Geological Disposal - Geosphere Status Report (NDA Report no. DSSC/453/01)," NDA, UK, Tech. Rep. December, 2016. [Online].

Available: https://rwm.nda.gov.uk/publication/geological-disposal-geosphere-status-report/?download.

[99] International Atomic Energy Agency, "Scientific and Technical Basis for the Geological Disposal of Radioactive Wastes," Vienna, Tech. Rep., 2003. [Online]. Available: https://www-pub.iaea.org/MTCD/Publications/PDF/TRS413_web.pdf.

[100] R. Metcalfe and S. Watson, "Technical issues associated with deep repositories for radioactive waste in different geological environments protecting and improving the environment in England and," Tech. Rep., 2009, p. 224. [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/291763/scho0809bqvu-e-e.pdf.

[101] Radioactive Waste Management Ltd., "Geological Disposal, Generic Environmental Safety Case (NDA Report no. DSSC/203/01)," NDA, NDA, UK, Tech. Rep., 2016, p. 275. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-generic-environmental-safety-case-main-report-december-2010/%20http://www.nda.gov.uk/aboutus/geological-disposal/rwmd-work/dssc/.

[102] British Geological Survey, "National Geological Screening : Northern England region (Commissioned Report CR/17/103)," British Geological Survey, Tech. Rep., 2018. [Online]. Available: https://www.bgs.ac.uk/download/ngs-northern-england/#.

[103] ——, "National Geological Screening: Wales (Commissioned Report CR/17/094)," British Geological Survey, Tech. Rep., 2018. [Online]. Available: https://www.bgs.ac.uk/download/ngs-wales/#.

[104] ——, "National Geological Screening: Northern Ireland (Commissioned Report CR/17/096)," British Geological Survey, Tech. Rep., 2018, pp. 1–9. [Online]. Available: https://www.bgs.ac.uk/download/ngs-northern-ireland/#.

[105] Radioactive Waste Management Ltd., "Geological Disposal - Concept Status Report," NDA, UK, Tech. Rep., 2017, p. 120. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-concept-status-report/?download.

[106] United Kingdom Nirex Limited, "Generic Repository Studies: Assessment of Repository Designs in Clays and Evaporites," Tech. Rep. 235, 2007, p. 245. [Online]. Available: https://rwm.nda.gov.uk/publication/generic-repository-studies-assessment-of-repository-designs-in-clays-and-evaporites/?download.

[107] R. Metcalfe, S. Watson, and T. McEwan, "Geosphere Parameters for Generic Geological Environments," RWM Ltd, Tech. Rep. Version 4, 2015. [Online]. Available: https://rwm.nda.gov.uk/publication/geosphere-parameters-for-generic-geological-environments/?download.

[108] Nagra, "Project Opalinus Clay Safety Report: Demonstration of disposal feasibility for spent fuel, vitrified high-level waste and long-lived intermediate-level waste (TR-02-05)," Tech. Rep., 2002. [Online]. Available: https://curie.ornl.gov/content/project-opalinus-clay-safety-report-demonstration-disposal-feasibility-spent-fuel-vitrified.

[109] P. Landais and J.-F. O. Aranyossy, "Clays in Natural and Engineered Barriers for Radioactive Waste Confinement," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 33, p. 40, 2008, ISSN: 1474-7065. [Online]. Available: https://books.google.co.uk/books?id=4b_IDgAAQBAJ&pg=PA40&lpg=PA40&dq=gdf+belgium+clay&source=bl&ots=QkTaAPIplS&sig=kQXYOYJ9HPn57FyDg1a6OOaMAOs&hl=en&sa=X&ved=0ahUKEwiujIT3yeHYAhVmF8AKHaeID00Q6AEINzAB#v=onepage&q=gdf%20belgium%20clay&f=false%20http://www.science.

[110] Radioactive Waste Management Ltd., "Geological Disposal: Generic Disposal Facility Design (NDA Report no. DSSC/412/01)," RWM, NDA, NDA, UK, Tech. Rep., 2016. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-generic-disposal-facility-designs/?download.

[111] J. Plant, D. Jones, H. Haslam, *et al.*, *The Cheshire Basin: Basin Evolution, Fluid Movement and Mineral Resources in a Permo-Triassic Rift Setting*, Keyworth, Nottingham,

2000. [Online]. Available: https://pubs.bgs.ac.uk/publications.html?pubID=B06159.

[112] Bundesgesellschaft für Endlagerung mbH (BGE), *Press Release- Gorleben mine will be closed*, 2021. [Online]. Available: https://www.bge.de/de/aktuelles/meldungen-und-pressemitteilungen/meldung/news/2021/9/645-gorleben/.

[113] Radioactive Waste Management Ltd., "Geological Disposal: National Geological Screening- Detailed Technical Instructions and Protocols (Technical Note no. 24600903)," RWM Ltd, NDA, UK, Tech. Rep., 2016. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/510689/national-geological-screening_detailed-technical-instructions-and-protocols.pdf.

[114] Nuclear Decommissioning Authority, "Design Information Requirements from the RWMD Site Characterisation Programme (NDA Technical Note no. 19656068)," Tech. Rep. 19656068, 2013. [Online]. Available: https://rwm.nda.gov.uk/publication/tn-18104-gd-design-information-requirements-from-the-rwmd-site-characterisation-programme/?download.

[115] International Organization for Standardization, "Geotechnical investigation and testing-Identificati description and classification of rock," Tech. Rep., 2017. [Online]. Available: https://www.iso.org/standard/66347.html.

[116] C.-L. Zhang, "Thermo-hydro-mechanical behavior of clay rock for deep geological disposal of high-level radioactive waste," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 10, no. 5, pp. 992–1008, 2018, ISSN: 16747755. DOI: 10.1016/j.jrmge.2018.03.006. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1674775517304390.

[117] D. Schofield, M. Lewis, P. Smedley, J. Bloomfield, and D. Boon, "Illustrative Components of the Geological Environment," British Geological Survey, Tech. Rep., 2014. [Online]. Available: http://nora.nerc.ac.uk/id/eprint/511272/1/CR14132N.pdf.

[118] M. Gysel, "Anhydrite Dissolution Phenomena: Three Case Histories of Anhydrite Karst Caused by Water Tunnel Operation," *Rock Mechanics and Rock Engineering*, vol. 35, no. 1, pp. 1–21, 2002, ISSN: 07232632. DOI: 10.1007/s006030200006. [Online]. Available: http://link.springer.com/10.1007/s006030200006.

[119] Radioactive Waste Management Ltd., "Geological Disposal: Generic Disposal Facility Designs (NDA Report no. NDA/RWMD/048)," NDA, UK, Tech. Rep. December, 2010. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-generic-disposal-facility-designs/.

[120] D. M. Reeves, R. Parashar, and Y. Zhang, "Hydrogeologic Characterisation of Fractured Rock Masses Intended for Disposal of Radioactive Waste," in *Radioactive Waste*, June 2014, 2012. DOI: 10.5772/1859. [Online]. Available: https://www.intechopen.com/chapters/36032.

[121] F. Bergaya, B. K. G. Theng, and G. Lagaly, *Handbook of Clay Science*, Volume 5, Elsevier Science, 2011, p. 259, ISBN: ISBN 10: 0080982581. [Online]. Available: https://www.elsevier.com/books/handbook-of-clay-science/bergaya/978-0-08-099364-5.

[122] V. Palchik and Y. H. Hatzor, "The Influence of Porosity on Tensile and Compressive Strength of Porous Chalks," *Rock Mechanics and Rock Engineering*, vol. 37, no. 4, pp. 331–341, 2004, ISSN: 0723-2632. DOI: 10.1007/s00603-003-0020-1.

[123] F. A. Caporuscio, H. Boukhalfa, M. C. Cheshire, A. B. Jordan, and M. Ding, "BRINE MIGRATION EXPERIMENTAL STUDIES FOR SALT REPOSITORIES," Tech. Rep., 2013. [Online]. Available: https://www.energy.gov/sites/prod/files/2013/12/f5/BrineMigrationinExpermntsSaltR1.pdf.

[124] Office for Nuclear Regulation, "Geological Disposal: Nuclear Safety Technical Assessment Guide," Tech. Rep., 2018. [Online]. Available: https://www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-101.pdf.

[125] C. L. Zhang, "Sealing of fractures in claystone," *Journal of Rock Mechanics and Geotechnical Engineering*, 2013, ISSN: 16747755. DOI: 10.1016/j.jrmge.2013.04.001.

[126] S. Horseman, J. Higgo, J. Alexander, and J. Harrington, "Water, gas and solute movement through argillaceous media (Nuclear Energy Agency Rep. CC-96/1)," Tech. Rep., 1996, p. 290. [Online]. Available: https://inis.iaea.org/search/search.aspx?orig_q=RN:28007514.

[127] S. T. Horseman, J. F. Harrington, D. J. Birchall, D. J. Noy, and R. J. Cuss, "Consolidation and rebound properties of Opalinus Clay: A long-term, fully-drained test (Technical Report CR/05/128)," British Geological Survey, Tech. Rep., 2005. [Online]. Available: http://nora.nerc.ac.uk/id/eprint/11314/.

[128] F. G. Bell, *Engineering Properties of Soils and Rocks.* Elsevier Science, 1992, p. 354, ISBN: eBook ISBN: 9781483102276. DOI: 10.1016/C2013-0-01182-6. [Online]. Available: https://www.elsevier.com/books/engineering-properties-of-soils-and-rocks/bell/978-0-7506-0489-5.

[129] M. Manga, "Origin of postseismic streamflow changes inferred from baseflow recession and magnitude-distance relations," *Geophysical Research Letters*, vol. 28, no. 10, pp. 2133–2136, 2001, ISSN: 00948276. DOI: 10.1029/2000GL012481. [Online]. Available: http://doi.wiley.com/10.1029/2000GL012481.

[130] R. Shaw, C. Auton, B. Baptie, *et al.*, "Potential Natural Changes and Implications for a UK GDF: Minerals and Waste Programme Commissioned Report CR/21/127N," British Geological Survey, Tech. Rep., 2013, pp. 1–175. [Online]. Available: http://nora.nerc.ac.uk/id/eprint/500752/1/CR12127N.pdf.

[131] D. Holton, M. Dickinson, A. Hoch, *et al.*, "Project Ankhiale : Disposability and full life cycle implications of high-heat generating UK wastes," NDA, UK, NDA, UK, Tech. Rep. 1, 2012. [Online]. Available: https://rwm.nda.gov.uk/publication/high-

heat-generating-wastes-ipt-roadmap-finalv2-nda-rwmd-095-tn_18043/?download.

[132] Radioactive Waste Management Ltd., "Geological Disposal: Engineered Barrier System Status Report (NDA Report no. DSSC/452/01)," RWM Ltd, NDA, UK, Tech. Rep., 2016. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-engineered-barrier-system-status-report/?download.

[133] A. I. Marsh, L. G. Williams, and J. A. Lawrence, "The important role and performance of engineered barriers in a UK geological disposal facility for higher activity radioactive waste," *Progress in Nuclear Energy*, vol. 137, 2021, ISSN: 01491970. DOI: 10.1016/j.pnucene.2021.103736. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0149197021001037.

[134] Nuclear Energy Agency, "Engineered Barrier Systems and the Safety of Deep Geological Repositories: State -of-the-art Report," Radioactive Waste Management, OECD Publishing, OECD Publishing, Paris, Tech. Rep., 2003. [Online]. Available: https://www.oecd-nea.org/jcms/pl_13634/engineered-barrier-systems-and-the-safety-of-deep-geological-repositories?details=true.

[135] M. White, T. Baldwin, T. Hicks, and P. Hooker, "Engineered Barrier Materials for Geological Disposal Facilities," Galson Sciences Ltd for the Nuclear Decommissioning Authority Radioactive Waste Management Directorate, Prepared by Galson Sciences Limited for NDA RWMD, UK, Tech. Rep. November, 2008. [Online]. Available: https://rwm.nda.gov.uk/publication/engineered-barrier-materials-for-geological-disposal-facilities/.

[136] NDA Waste & Nuclear Materials Unit, *Letter of Compliance (LoC) Assessment Process (W&NM/PP/011)*, 2008. [Online]. Available: https://rwm.nda.gov.uk/publication/wnm-pp-011-letters-of-compliance-loc-assessment-process-1-january-2008/?download.

[137] E. Curti, J. Crovisier, G. Morvan, and A. Karpoff, "Long-term corrosion of two nuclear waste reference glasses (MW and SON68): A kinetic and mineral alteration study," *Applied Geochemistry*, vol. 21, no. 7, pp. 1152–1168, 2006, ISSN: 08832927. DOI: 10.1016/j.apgeochem.2006.03.010. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0883292706001132.

[138] Radioactive Waste Management Ltd., "Geological Disposal: Waste Package Accident Performance Status Report (NDA Report no. DSSC/457/01)," NDA, UK, Tech. Rep. 7, 2016, p. 1297. DOI: 10.1097/00000446-198107000-00016.

[139] J. H. Sharp, J. Hill, N. B. Milestone, and E. W. Miller, "Cementitious systems for encapsulation of intermediate level waste," in *Proceedings of ICEM '03: The 9th International Conference on Radioactive Waste Management and Environmental Remediation, ICEM*, vol. 3, Oxford, 2003, pp. 1425–1433. DOI: 10.1115/ICEM2003-4554. [Online]. Available: http://isl.group.shef.ac.uk/papers/NBMICEM03paper.pdf.

[140] International Atomic Energy Agency, "Spent Fuel Performance Assessment and Research - Final Report of a Coordinated Research Project (SPAR-II) (IAEA-TECDOC-1680 S)," IAEA, Vienna, Tech. Rep., 2012, IAEA-TECDOC–1680. [Online]. Available: http://www-pub.iaea.org/MTCD/Publications/PDF/TE_1680_web.pdf.

[141] F. King, "Corrosion Resistance of Austenitic and Duplex Stainless Steels in Environments Related to UK Geological Disposal (QRS-1384C-R1)," Prepared by Quintessa Limited for NDA RWMD, UK, Tech. Rep. QRS-1384C-R1, 2009, pp. 5–28. [Online]. Available: https://rwm.nda.gov.uk/publication/corrosion-resistance-of-austenitic-and-duplex-stainless-steels-in-environments-related-to-uk-geological-disposal/.

[142] Radioactive Waste Management Ltd., "Waste Package Specification and Guidance Documentation: Guidance on the design of waste containers for waste packages containing low heat generating waste (WPS/890/01)," Tech. Rep. December, 2019,

pp. 1–123. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/876830/WPS_890_01_Guidance_on_the_design_of_waste_containers_for_waste_packages_containing_low_heat_generating_waste.pdf.

[143] Ontario Power Generation, "Reference Low and Intermediate Level Waste Inventory for the Deep Geological Repository, (Report No. 00216-REP-03902-00003 R003)," OPG, Ontario, Canada, Tech. Rep. December, 2010. [Online]. Available: https://www.ceaa.gc.ca/050/documents_staticpost/17520/49820/inventory.pdf.

[144] D. Nixon, A. Tuxworth, C. Leung, V. Smith, A. Turnbull, and N. Smart, "Atmospheric durability of coating systems and the potential for internal corrosion , pressurisation and hydrogen embrittlement of carbon steel and cast iron ILW / LLW containers," Amec Foster Wheeler plc, Amec Foster Wheeler Plc, Oxfordshire, Tech. Rep. 2, 2016.

[145] N. G. Hunt, P. Gierszewski, E. Kremer, and S. Russell, "Used fuel repository post-closure safety assessment in crystalline rock (NEA/RWM/R(2013)9)," NEA OECD, Tech. Rep., 2014. [Online]. Available: https://inis.iaea.org/collection/NCLCollectionStore/_Public/46/027/46027334.pdf.

[146] R. Patel, C. Punshon, J. Nicholas, *et al.*, "Technical Report 12-06: Canister Design Concepts for Disposal of Spent Fuel and High Level Waste," Nagra, Switzerland, Tech. Rep., 2012. [Online]. Available: https://www.osti.gov/etdeweb/biblio/22145939.

[147] Radioactive Waste Management Ltd., "Geological Disposal: Gas Status Report (NDA Report no. DSSC/455/01)," NDA, UK, Tech. Rep. December, 2016. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-gas-status-report/?download.

[148] R. G. Vasconcelos, N. Beaudoin, A. Hamilton, N. C. Hyatt, J. L. Provis, and C. L. Corkhill, "Characterisation of a high pH cement backfill for the geological disposal of nuclear waste: The Nirex Reference Vault Backfill," *Applied Geochemistry*, vol. 89, pp. 180–189, 2018, ISSN: 0883-2927. DOI: 10.1016/J.APGEOCHEM.2017.11.007.

[Online]. Available: https://www.sciencedirect.com/science/article/pii/S0883292717302548.

[149] R. G. Vasconcelos, A. Idiart, N. C. Hyatt, J. L. Provis, and C. L. Corkhill, "Leaching of Nirex Reference Vault Backfill cement by clay, granite and saline groundwaters," *MRS Advances*, vol. 3, no. 21, pp. 1175–1180, 2018, ISSN: 2059-8521. DOI: 10.1557/adv.2018.248. [Online]. Available: https://www.cambridge.org/core/product/identifier/S2059852118002487/type/journal_article.

[150] M. C. Alonso and J. L. Garcia-Siñeriz, "Engineering Feasibility For The Fabrication And Emplacement Of Cementitious Repository Materials : Results From The Ec-Esdred Project (NEA/RWM/R(2012)3/REV)," in *A workshop organised by the OECD/NEA Integration Group in the Safety Case and hosted by ONDRAF/NIRAS*, 2012, pp. 61–64. [Online]. Available: https://inis.iaea.org/collection/NCLCollectionStore/_Public/46/133/46133918.pdf?r=1.

[151] B. Swift, P. Bamforth, A. Hoch, C. Jackson, D. Roberts, and G. Baston, "Cracking , Flow and Chemistry in NRVB," Serco for NDA RWMD, Prepared by Serco for NDA RWMD, UK, Tech. Rep. 3, 2010, p. 155. [Online]. Available: https://rwm.nda.gov.uk/publication/tn-17701-serco_tas_000505_001_cracking_flow_and_chemistry_in_nrvb_issue_3/?download.

[152] J. Wilson, S. Benbow, and R. Metcalfe, "Understanding the long-term evolution of cement backfills: alteration of NRVB due to reaction with groundwater solutes (RWM/03/043)," Prepared by AMEC for RWM Ltd, UK, Tech. Rep. March, 2017, pp. 1–132. [Online]. Available: https://rwm.nda.gov.uk/publication/understanding-the-long-term-evolution-of-cement-backfills-alteration-of-nrvb-due-to-reaction-with-groundwater-solutes/?download.

[153] M. Anwar and M. Roushdi, "Improved concrete properties to resist the saline water using environmental by-product," *Water Science*, vol. 27, no. 54, pp. 30–38, 2013,

ISSN: 1110-4929. DOI: 10.1016/j.wsj.2013.12.003. [Online]. Available: http://dx.doi.org/10.1016/j.wsj.2013.12.003.

[154] T. Baldwin, N. Chapman, and F. Neall, "Geological Disposal Options for High-Level Waste and Spent Fuel," NDA, UK, Tech. Rep., 2008. [Online]. Available: https://www.davidsmythe.org/nuclear/baldwin%20etal2008%20Geological-Disposal-Options-for-High-Level-Waste-and-Spent-Fuel-January-2008.pdf.

[155] Radioactive Waste Management Ltd., "Geological Disposal: Science and Technology Plan 2020 (NDA/RWM/167)," NDA, UK, Tech. Rep. October, 2020. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/931865/Science_and_Technology_Plan_2020.pdf.

[156] M. J. White and D. Hutchinson, "Generic Specification for Waste Packages Containing High Heat Generating Waste: Impact of Geological Disposal Concepts on Packaging Criteria," Tech. Rep., 2013. [Online]. Available: https://rwm.nda.gov.uk/publication/generic-specification-for-waste-packages-containing-hhgw-impacts-of-gd-concepts-on-packaging-criteria/?download.

[157] S. Rolland, M. Tribet, P. Jollivet, *et al.*, "Influence of gamma irradiation effects on the residual alteration rate of the French SON68 nuclear glass," *Journal of Nuclear Materials*, vol. 433, no. 1-3, pp. 382–389, 2013, ISSN: 00223115. DOI: 10.1016/j.jnucmat.2012.10.001. [Online]. Available: http://dx.doi.org/10.1016/j.jnucmat.2012.10.001.

[158] W. J. Weber, "Radiation and Thermal Ageing of Nuclear Waste Glass," *Procedia Materials Science*, vol. 7, pp. 237–246, 2014, ISSN: 22118128. DOI: 10.1016/j.mspro.2014.10.031. [Online]. Available: http://dx.doi.org/10.1016/j.mspro.2014.10.031.

[159] S. Peuget, J. M. Delaye, and C. Jégou, "Specific outcomes of the research on the radiation stability of the French nuclear glass towards alpha decay accumulation,"

Journal of Nuclear Materials, vol. 444, no. 1-3, pp. 76–91, 2014, ISSN: 00223115. DOI: 10.1016/j.jnucmat.2013.09.039. [Online]. Available: http://dx.doi.org/10.1016/j.jnucmat.2013.09.039.

[160] J. M. Schofield, S. W. Swanton, B. Farahani, *et al.*, "Experimental studies of the chemical durability of UK HLW and ILW glasses (RWM005105)," Prepared by AMEC for RWM Ltd, UK, Tech. Rep. 01, 2016, pp. 1–241. [Online]. Available: https://rwm.nda.gov.uk/publication/experimental-studies-of-the-chemical-durability-of-uk-hlw-and-ilw-glasses-interim-progress-report-amec103498ipr02-revision-3/.

[161] E. J. Harvey, M. J. White, J. Mackenzie, I. McKinley, and S. Watson, "Geological Disposal Concept Options for Vitrified HLW," RWMD, NDA, Prepared by Galson Sciences for NDA RWMD, UK, Tech. Rep. December, 2012. [Online]. Available: https://tools.nda.gov.uk/publication/geological-disposal-concept-options-for-vitrified-hlw/.

[162] A. Craven, "Review of wasteform ageing up to repository saturation (Part One) (WMT(06)P118)," Report by Waste Management Technology for NDA RWMD, UK, Tech. Rep. 1, 2010. [Online]. Available: https://rwm.nda.gov.uk/publication/review-of-wasteform-ageing-up-to-repository-restaturation-part-one/.

[163] ——, "Review of wasteform ageing up to repository saturation (Part Two) (WMT(07)P052)," NDA, UK, Report by Waste Management Technology for NDA RWMD, UK, Tech. Rep. 1, 2010. [Online]. Available: https://rwm.nda.gov.uk/publication/review-of-wasteform-ageing-up-to-repository-resaturation-part-two-september-2010/.

[164] International Atomic Energy Agency, "Improved Cement Solidification of Low and Intermediate Level Radioactive Wastes (IAEA-TECDOC-929)," IAEA, IAEA, Vienna, Tech. Rep., 1992. [Online]. Available: https://www.iaea.org/publications/

1454/improved-cement-solidification-of-low-and-intermediate-level-radioactive-wastes.

[165] I. Richardson, G. Groves, and C. Wilding, "Effect of γ-Radiation on the Microstructure and Microchemistry of ggbfs/OPC Cement Blends," *MRS Proceedings*, vol. 176, no. 31, 1989, ISSN: 0272-9172. DOI: 10.1557/proc-176-31. [Online]. Available: https://www.cambridge.org/core/product/identifier/S1946427400373213/type/journal_article.

[166] C. R. Wilding, D. C. Phillips, and C. Lyon, "The Effects of Radiation on Intermediate Level Waste Forms," *MRS Proceedings*, vol. 127, pp. 513–518, 1988, ISSN: 0272-9172. DOI: 10.1557/PROC-127-513. [Online]. Available: https://www.cambridge.org/core/product/identifier/S1946427400540032/type/journal_article.

[167] C. Wilding, "The performance of cement based systems," *Cement and Concrete Research*, vol. 22, no. 2-3, pp. 299–310, 1992, ISSN: 0008-8846. DOI: 10.1016/0008-8846(92)90069-8. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0008884692900698.

[168] R. O. Abdel Rahman and M. I. Ojovan, "Leaching Tests and Modelling of Cementitious Wasteforms Corrosion," *Innovations in Corrosion and Materials Science*, vol. 4, no. 2, pp. 90–95, 2014, ISSN: 23520949. DOI: 10.2174/23520949046661411262216 26.

[169] M. I. Ojovan, G. A. Varlackova, Z. I. Golubeva, and O. N. Burlaka, "Long-term field and laboratory leaching tests of cemented radioactive wastes," *Journal of Hazardous Materials*, vol. 187, no. 1-3, pp. 296–302, 2011, ISSN: 0304-3894. DOI: 10.1016/J.JHAZMAT.2011.01.004. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0304389411000264.

[170] D. Roy, B. Scheetz, L. Wakeley, and M. Barnes, "Leach characterization of cement encapsulated wastes," *Nuclear and Chemical Waste Management*, vol. 3, no. 1, pp. 35–42, 1982, ISSN: 0191-815X. DOI: 10.1016/0191-815X(82)90026-2. [Online]. Available: https://www.sciencedirect.com/science/article/pii/0191815X82900262.

[171] L. Chuang, T. Kajio, E. Owaki, Y. Morinaga, Y. Elakeswaran, and T. Nawa, "Sulphate attack in slag-blended cementitious materials hydrated with sodium sulphate," in *Fifth International Conference on Sustainable Construction Materials and Technologies*, vol. 2, 2019. [Online]. Available: http://www.claisse.info/Proceedings.htm.

[172] Y. Elakneswaran, E. Owaki, and T. Nawa, "Modelling Long-Term Durability Performance of Cementitious Materials under Sodium Sulphate Interaction," *Applied Sciences*, vol. 8, no. 12, p. 2597, 2018. DOI: 10.3390/app8122597.

[173] W. Gashier, T. Miura, K. Hashimoto, R. J. Hand, and H. Kinoshita, "Leaching behaviour of cementitious nuclear wasteforms containing caesium and strontium," *Advances in Applied Ceramics*, vol. 113, no. 8, pp. 447–452, 2014, ISSN: 17436761. DOI: 10.1179/1743676114Y.0000000146. [Online]. Available: http://eprints.whiterose.ac.uk/97728/http://www.tandfonline.com/10.1179/1743676114Y.0000000146.

[174] K. Law, S. Parry, N. Bryan, *et al.*, "Plutonium Migration during the Leaching of Cemented Radioactive Waste Sludges," *Geosciences*, vol. 9, no. 1: 31, 2019. DOI: 10.3390/geosciences9010031.

[175] R. J. Caldwell, N. J. Bowmer, E. J. Butcher, and I. H. Godfrey, "Characterisation of Full-Scale Inactive Cement-Based Intermediate Level Nuclear Wasteforms After One Decade of Storage," in *12th International Conference on Nuclear Engineering, Volume 2*, ASME, 2004, pp. 681–689, ISBN: 0-7918-4688-1. DOI: 10.1115/ICONE12-49072. [Online]. Available: http://proceedings.asmedigitalcollection.asme.org/proceeding.aspx?articleid=1650055.

[176] M. Cowper, C. Askeljung, A. Puranen, *et al.*, "Scoping Studies of the Matrix Dissolution Rate and Instant Release Fraction of Spent AGR Fuel (RWM005264L)," Report by AMEC Foster Wheeler for RWM Ltd, UK., Tech. Rep. RWM005264L, 2016. [Online]. Available: https://rwm.nda.gov.uk/publication/scoping-studies-of-the-

matrix-dissolution-rate-and-instant-release-fraction-of-spent-agr-fuel-main-report/?download.

[177] D. W. Shoesmith, "Chemistry/Electrochemistry of Spent Nuclear Fuel As A Wasteform," in *Uranium: Cradle to Grave*, 43, Mineralogical Society of Canada, 2013, ch. 11, pp. 1–32, ISBN: 978-0-921294-53-5.

[178] G. Rossiter and M. Mignanelli, "The characteristics of LWR fuel at high burnup and their relevance to AGR spent fuel (NNL (10) 10930)," NNL (10) 10930, Prepared by NNL for NDA, UK, Tech. Rep. 2, 2010, pp. 1–60. [Online]. Available: https://rwm.nda.gov.uk/publication/the-characteristics-of-lwr-fuel-at-high-burnup-and-their-relevance-to-agr-spent-fuel/.

[179] T. Sakuragi, S. Yoshida, O. Kato, and T. Tateishi, "Study of stainless steel corrosion by hydrogen measurement under deoxygenated, low-temperature and basic repository conditions," *Progress in Nuclear Energy*, vol. 87, pp. 26–31, 2016, ISSN: 0149-1970. DOI: 10.1016/J.PNUCENE.2015.10.008. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0149197015300883#bib5.

[180] F. King, "Durability of High Level Waste and Spent Fuel Disposal Containers – an overview of the combined effect of chemical and mechanical degradation mechanisms: Appendix B.4- Corrosion of Stainless Steel (17697/TR/03)," NDA, Prepared by AMEC for the NDA RWMD, UK, Tech. Rep., 2014. [Online]. Available: https://rwm.nda.gov.uk/publication/durability-of-high-level-waste-and-spent-fuel-disposal-containers-appendix-b4-corrosion-of-stainless-steel/.

[181] C. Anwyl, C. Boxall, R. Wilbraham, D. Hambley, and C. Padovani, "Corrosion of AGR Fuel Pin Steel Under Conditions Relevant to Permanent Disposal," *Procedia Chemistry*, vol. 21, pp. 247–254, 2016, ISSN: 18766196. DOI: 10.1016/j.proche.2016.10.035.

[182] A. Al-Shater, D. Engelberg, S. Lyon, *et al.*, "Characterization of the stress corrosion cracking behavior of thermally sensitized 20Cr-25Ni stainless steel in a simulated cooling pond environment," *Journal of Nuclear Science and Technology*, vol. 54, no. 7,

pp. 742–751, 2017, ISSN: 0022-3131. DOI: 10.1080/00223131.2017.1309305. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/00223131.2017.1309305.

[183] G. Knowles, "Corrosion of sensitized advanced gas reactor fuel cladding in moist air: Evidence for incubation periods before the onset of intergranular cracking," in *Effects of radiation and environmental factors on the durability of materials in spent fuel storage and disposal (IAEA-TECDOC-1316)*, IAEA, Vienna, 2002, pp. 7–16, ISBN: 9201138024. [Online]. Available: https://inis.iaea.org/search/search.aspx?orig_q=RN:34018059.

[184] C. Taylor, "The formation of sensitised microstructures during the irradiation of CAGR fuel pin cladding," in *Proceedings of the Radiation-induced Sensitisation of Stainless Steels*, Berkeley, UK, 1986. [Online]. Available: https://inis.iaea.org/search/search.aspx?orig_q=RN:18098354.

[185] C. Degueldre, J. Fahy, O. Kolosov, *et al.*, "Mechanical Properties of Advanced Gas-Cooled Reactor Stainless Steel Cladding After Irradiation," *Journal of Materials Engineering and Performance*, vol. 27, no. 5, pp. 2081–2088, 2018, ISSN: 15441024. DOI: 10.1007/s11665-018-3323-9.

[186] S. Swanton, B. Swift, A. Adeogun, M. Plews, and N. Smart, "Carbon-14 Project Team Phase 2: Irradiated Steel Wastes (RWM005675)," AMEC, Prepared by AMEC for RWM Ltd, UK, Tech. Rep. 1, 2016. [Online]. Available: https://rwm.nda.gov.uk/publication/carbon-14-project-team-phase-2-irradiated-steel-wastes/.

[187] International Atomic Energy Agency, "Durability of spent nuclear fuels and facility components in wet storage (IAEA-TECDOC-1012)," IAEA, IAEA, Vienna, Tech. Rep., 1998. [Online]. Available: https://www-pub.iaea.org/MTCD/publications/PDF/te_1012_prn.pdf.

[188] R. B. Rebak, "The long-term environmental degradation of zirconium alloys in contact with spent nuclear fuel: A Review," *American Society of Mechanical Engineers,*

Pressure Vessels and Piping Division (Publication) PVP, vol. 7, pp. 209–214, 2008, ISSN: 0277027X. DOI: 10.1115/PVP2008-61272.

[189] D. W. Shoesmith and D. Zagidulin, "The corrosion of zirconium under deep geologic repository conditions," *Journal of Nuclear Materials*, vol. 418, no. 1-3, pp. 292–306, 2011, ISSN: 00223115. DOI: 10.1016/j.jnucmat.2011.07.028.

[190] G. Bellanger and J. J. Rameau, "Inhibition of chloride pitting corrosion of Zircaloy-4 alloy in highly radioactive water by radiolytic nitrate and hydrogen peroxide," *Journal of Materials Science*, vol. 35, no. 7, pp. 1759–1771, 2000, ISSN: 00222461. DOI: 10.1023/A:1004732703500. [Online]. Available: http://link.springer.com/10.1023/A:1004732703500.

[191] T. Motooka, A. Komatsu, T. Tsukada, and M. Yamamoto, "Effect of gamma radiolysis on pit initiation of zircaloy-2 in water containing sea salt," *Journal of Nuclear Science and Technology*, vol. 51, no. 7-8, pp. 987–995, 2014, ISSN: 00223131. DOI: 10.1080/00223131.2014.907550. [Online]. Available: http://dx.doi.org/10.1080/00223131.2014.907550.

[192] C. Yan, R. Wang, Y. Wang, X. Wang, and G. Bai, "Effects of ion irradiation on microstructure and properties of zirconium alloys-A review," *Nuclear Engineering and Technology*, vol. 47, no. 3, pp. 323–331, 2015, ISSN: 2234358X. DOI: 10.1016/j.net.2014.12.015.

[193] S. Necib, N. Diomidis, P. Keech, and M. Nakayama, "Corrosion of carbon steel in clay environments relevant to radioactive waste geological disposals, Mont Terri rock laboratory (Switzerland)," *Swiss Journal of Geosciences*, vol. 110, no. 1, pp. 329–342, 2017, ISSN: 16618734. DOI: 10.1007/s00015-016-0259-7.

[194] Nuclear Decommissioning Authority, "Geological Disposal. Waste Package Specification for 500 litre drum waste packages (WPSGD No. WPS/300/03)," NDA, UK, Tech. Rep. WPSGD No. WPS/300/03, 2013. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/

file/935719/WPS_300_04_Part_D_-_Specification_for_Waste_Packages_Containing_Low_Heat_Generating_Waste.pdf.

[195] N. Smart, "Review of Effect of Chloride on Corrosion of Stainless Steels in Cementitious Environments (TE2910/006)," Prepared by Serco for NDA, UK, Tech. Rep. 3, 2010. [Online]. Available: https://rwm.nda.gov.uk/publication/review-of-effect-of-chloride-on-corrosion-of-stainless-steels-in-cementitious-environments/.

[196] F. King, "Review of the corrosion performance of selected metals as canister materials for UK spent fuel and or HLW- Appendix F: Corrosion of Stainless Steels (QRS-1384J-1)," NDA RWMD, UK, Tech. Rep., 2009. [Online]. Available: https://rwm.nda.gov.uk/publication/review-of-the-corrosion-performance-of-selected-metals-as-canister-materials-for-uk-spent-fuel-and-or-hlw/?download.

[197] B. Kursten, E. Smailos, I. Azkarate, L. Werme, N. Smart, and G. Santarini, "COBECOMA: state of art document on the COrrosion BEhaviour of COntainer MAterials.," 5th Euratom Framework Programme 1998-2002, Luxemburg, Tech. Rep. contract no. FIKW-CT-20014-20138 final report, 2004. [Online]. Available: https://cordis.europa.eu/docs/projects/files/FIKW/FIKW-CT-2001-20138/97258971-6_en.pdf.

[198] T. Fujii, T. Furumoto, K. Tohgo, and Y. Shimamura, "Crystallographic evaluation of susceptibility to intergranular corrosion in austenitic stainless steel with various degrees of sensitization," *Materials*, vol. 13, no. 3, 2020, ISSN: 19961944. DOI: 10.3390/ma13030613.

[199] O. Karnland, S. Olsson, A. Dueck, *et al.*, "Long term test of buffer material at the Äspö Hard Rock Laboratory, LOT project Final report on the A2 test parcel (TR-09-29)," SKB, Stockholm, Tech. Rep., 2009. [Online]. Available: https://www.osti.gov/etdeweb/servlets/purl/1030187.

[200] C. Svemar, L.-E. Johannesson, P. Grahm, *et al.*, "Prototype Repository: Opening and retrieval of outer section of Prototype Repository at Äspö Hard Rock Laboratory Summary report (TR-13-22)," SKB, SKB, Stockholm, Tech. Rep. January 2016, 2016. [Online]. Available: http://www.skb.com/publication/2483674/TR-13-22.pdf.

[201] B. Rosborg, "Recorded corrosion rates on copper electrodes in the Prototype Repository at the Äspö HRL (R-13-13)," SKB, Stockholm, Tech. Rep., 2013. [Online]. Available: https://skb.se/publication/2585798/R-13-13.pdf.

[202] N. R. Smart, A. Rance, B. Reddy, P. Fennell, and R. Winsley, "Analysis of SKB MiniCan-Experiment 3 (TR-12-09)," SKB, Stockholm, Tech. Rep. 32, 2012. [Online]. Available: https://www.skb.se/publikation/2571281/TR-12-09.pdf.

[203] N. R. Smart, A. P. Rance, B. Reddy, L. Hallbeck, K. Pedersen, and A. J. Johansson, "In situ evaluation of model copper-cast iron canisters for spent nuclear fuel: a case of microbiologically influenced corrosion (MIC)," *Corrosion Engineering, Science and Technology*, vol. 49, no. 6, pp. 548–553, 2014. DOI: 10.1179/1743278214Y.0000000213. [Online]. Available: https://www.tandfonline.com/doi/full/10.1179/1743278214Y.0000000213.

[204] N. Taniguchi and M. Kawasaki, "Influence of sulfide concentration on the corrosion behavior of pure copper in synthetic seawater," *Journal of Nuclear Materials*, vol. 379, no. 1-3, pp. 154–161, 2008. DOI: 10.1016/j.jnucmat.2008.06.010. [Online]. Available: https://ac.els-cdn.com/S0022311508003383/1-s2.0-S0022311508003383-main.pdf?_tid=3a300e5a-37ac-4ad4-903d-827e2198c3ca&acdnat=1535108543_ff4405bd3869fb05ec6331d1b0ef1a8c.

[205] Nacka Tingsträtt, *Mark- och miljödomstolens yttrande (Dok.Id 447298)*, Nacka, Sweden, 2018. [Online]. Available: https://www.regeringen.se/4ada4f/globalassets/regeringen/dokument/miljodepartementet/pdf/m1333-11-yttrande-till-regeringen-2018-01-23.pdf.

[206] K. Pettersson, "A review of the creep ductility of copper for nuclear waste canister application (Technical Note 2012:13)," Swedish Radiation Safety Authority (SSM), Sweden, Tech. Rep., 2011. [Online]. Available: https://www.stralsakerhetsmyndigheten.se/contentassets/3708a71f5d244468ae71b1599fb667c9/201213-technical-note-a-review-of-the-creep-ductility-of-copper-for-nuclear-waste-canister-application.

[207] P. Szakálos, "Corrosion of copper canister (Technical Note 2012:17)," Swedish Radiation Safety Authority (SSM), Sweden, Tech. Rep., 2012. [Online]. Available: https://inis.iaea.org/collection/NCLCollectionStore/_Public/43/128/43128053.pdf.

[208] T. Hedman, A. Nyström, and C. Thegerström, "Swedish containers for disposal of spent nuclear fuel and radioactive waste," *Comptes Rendus Physique*, vol. 3, no. 7-8, pp. 903–913, 2002, ISSN: 16310705. DOI: 10.1016/S1631-0705(02)01378-6. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1631070502013786.

[209] O. Karnland, S. Olsson, and U. Nilsson, "Mineralogy and sealing properties of various bentonites and smectite-rich clay materials (TR-06-30)," SKB, SKB, Stockholm, Tech. Rep., 2006, pp. 1–112. [Online]. Available: https://www.skb.se/publication/1419144/TR-06-30.pdf.

[210] Nuclear Decommissioning Authority, "Geological Disposal: A Review of the Development of Bentonite Barriers in the KBS 3V Disposal Concept (NDA Technical Note no. 21665941)," NDA, UK, Tech. Rep., 2014. [Online]. Available: https://rwm.nda.gov.uk/publication/a-review-of-the-development-of-bentonite-barriers-in-the-kbs-3v-disposal-concept/.

[211] M. V. Villar, "FEBEX-DP Post-mortem THM/THG Analysis Report (Arbeitsbericht NAB 16-17)," Nagra, Switzerland, Nagra, Switzerland, Tech. Rep., 2017. [Online]. Available: http://documenta.ciemat.es/bitstream/123456789/1122/1/NAB%2016-17%20FEBEX-DP%20Post-mortem%20THM-THG%20Analysis%20Report.pdf.

[212] M. V. Villar, R. J. Iglesias, C. Gutiérrez-Álvarez, and B. Carbonell, "Hydraulic and mechanical properties of compacted bentonite after 18 years in barrier conditions," *Applied Clay Science*, vol. 160, pp. 49–57, 2018, ISSN: 0169-1317. DOI: 10.1016/j.clay.2017.12.045. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S016913171730594X#bb0140.

[213] L.-E. Johannesson, L. Börgesson, R. Goudarzi, T. Sandén, D. Gunnarsson, and C. Svemar, "Prototype repository: A full scale experiment at Äspö HRL," *Physics and Chemistry of the Earth*, vol. 32, no. 1-7, pp. 58–76, 2007, ISSN: 1474-7065. DOI: 10.1016/J.PCE.2006.04.027. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1474706506002427.

[214] Svensk Kärnbränslehantering AB, "Design, production and initial state of the buffer. (TR-10-15)," SKB, SKB, Stockholm, Tech. Rep. December, 2010, p. 84. [Online]. Available: http://www.skb.se/upload/publications/pdf/TR-10-15.pdf.

[215] S. Olsson, V. Jensen, L.-E. Johannesson, *et al.*, "Prototype Repository: Hydro-mechanical, chemical and mineralogical characterization of the buffer and tunnel backfill material from the outer section of the Prototype Repository (TR-13-21)," SKB, Stockholm, Tech. Rep., 2013. [Online]. Available: https://www.skb.com/publication/2477824/TR-13-21.pdf.

[216] L. P. Meier and G. Kahr, "Determination of the Cation Exchange Capacity (CEC) of Clay Minerals Using the Complexes of Copper(II) Ion with Triethylenetetramine and Tetraethylenepentamine," *Clays and Clay Minerals*, vol. 47, no. 3, pp. 386–388, 1999, ISSN: 0009-8604. DOI: 10.1346/ccmn.1999.0470315.

[217] A. Muurinen, "Measurements on Cation Exchange Capacity of Bentonite in the Long-term Test of Buffer Material (LOT) (Working Report 2011-10)," Posiva Oy, Posiva Oy, Finland, Tech. Rep., 2011. [Online]. Available: http://www.posiva.fi/files/1983/WR_2011-10web.pdf.

[218] M. Ochs and C. Talerico, "SR-Can: Data and uncertainty assessment- Migration parameters for the bentonite buffer in the KBS-3 concept (TR-04-18)," SKB, SKB, Stockholm, Tech. Rep., 2004. [Online]. Available: https://inis.iaea.org/collection/NCLCollectionStore/_Public/36/030/36030954.pdf.

[219] M. Holmboe, K. Karin Norrfors, M. Jonsson, and S. Wold, "Effect of γ-radiation on Radionuclide Retention in Compacted Bentonite," *Radiation Physics and Chemistry*, vol. 80, no. 12, pp. 1371–1377, 2011. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:418866/FULLTEXT01.pdf.

[220] E. J. Butcher, J. Borwick, N. Collier, and S. J. Williams, "Long term leachate evolution during flow-through leaching of a vault backfill (NRVB)," *Mineralogical Magazine*, vol. 76, no. 8, pp. 3023–3031, 2012, ISSN: 0026-461X. DOI: 10.1180/minmag.2012.076.8.18. [Online]. Available: https://www.cambridge.org/core/product/identifier/S0026461X0001077X/type/journal_article.

[221] P. B. Bamforth, G. M. N. Baston, J. A. Berry, *et al.*, "Cement materials for use as backfill, sealing and structural materials in geological disposal concepts . A review of current status," Report prepared by Serco for NDA RWMD, UK, Prepared by Serco for NDA RWMD, UK, Tech. Rep. RP0618-252A, 2012, pp. 1–235. [Online]. Available: https://rwm.nda.gov.uk/publication/serco-005125_001-cement-review-final-31-may-2012-issue-3/.

[222] R. Guillaumont, T. Fanghänel, V. Neck, *et al.*, "Update on the Chemical Thermodynamics of Uranium, Neptunium, Plutonium, Americium and Technetium," in *Chemical Thermodynamics*, Amsterdam, Netherlands: Elsevier, 2003, pp. 1–918. [Online]. Available: https://www.oecd-nea.org/dbtdb/pubs/vol5-update-combo.pdf.

[223] G. Baston, M. M. Cowper, and T. A. Marshall, "Sorption of Np , Zr and Sn onto Leached and Hydrothermally-aged NRVB," Report prepared by Serco for NDA RWMD, UK., Prepared by Serco for NDA RWMD, UK., Tech. Rep. NPO003013, 2010. [Online].

Available: https://rwm.nda.gov.uk/publication/sorption-of-np-zr-and-sn-onto-leached-and-hydrothermally-aged-nrvb/.

[224] A. Harris, A. Atkinson, and P. Claisse, "Transport of gases in concrete barriers," *Waste Management*, vol. 12, no. 2-3, pp. 155–178, 1992, ISSN: 0956053X. DOI: 10.1016/0956-053X(92)90046-L. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/0956053X9290046L.

[225] D. Heyes, E. Butcher, J. Borwick, *et al.*, "Demonstration of Carbonation of the NRVB (NNL (14) 13296)," Prepared by NNL Ltd for RWM Ltd, UK, Tech. Rep. 4, 2015. [Online]. Available: https://rwm.nda.gov.uk/publication/demonstration-of-carbonation-of-the-nrvb/.

[226] G. Purser, A. E. Milodowski, J. F. Harrington, C. A. Rochelle, A. Butcher, and D. Wagner, "Modification to the flow properties of repository cement as a result of carbonation," *Procedia Earth and Planetary Science*, vol. 7, pp. 701–704, 2013. DOI: 10.1016/j.proeps.2013.03.102. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1878522013001835?via%3Dihub.

[227] K.-P. Krohn, D. Stuhrenberg, M. Jobmann, *et al.*, "Mechanical and hydraulic behaviour of compacting crushed salt backfill at low porosities. Project REPOPERM. Phase 2 (GRS-450)," Prepared by BGR, DBE TEC, GRS gGmbH, for BMWi, Germany, Tech. Rep., 2017. [Online]. Available: https://www.grs.de/sites/default/files/pdf/grs-450_1.pdf.

[228] W. Betchtold, E. Smailos, S. Heusermann, *et al.*, "Backfilling and sealing of underground repositories for radioactive waste in salt (Bambus II project)," European Commission, EN CEC, Belgium, Tech. Rep., 2004. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/68558bff-d5d4-4202-814a-94b3a2ecee68.

[229] S. Bauer and A. Urquhart, "Thermal and physical properties of reconsolidated crushed rock salt as a function of porosity and temperature," *Acta Geotechnica*, vol. 11, no. 4,

pp. 913–924, 2016, ISSN: 1861-1125. DOI: 10.1007/s11440-015-0414-8. [Online]. Available: http://link.springer.com/10.1007/s11440-015-0414-8.

[230] S. Khamrat, S. Somtong, and K. Fuenkajorn, "Consolidation of crushed salt backfill for salt and potash mines," in *ISRM VietRock 2015 International Workshop*, vol. 2015-March, Hanoi: International Society for Rock Mechanics and Rock Engineering, 2015, p. 505, ISBN: 9786049133725. [Online]. Available: https://www.onepetro.org/conference-paper/ISRM-VIETROCK-2015-011.

[231] D. Stuhrenberg and O. Schulze, "Porosity and permeability of crushed rock salt during compaction," in *Mechanical Behaviour of Salt VII*, CRC Press, 2012, pp. 275–282, ISBN: 020310076X. [Online]. Available: https://books.google.co.uk/books?hl=en&lr=&id=AEbLBQAAQBAJ&oi=fnd&pg=PA275&dq=Porosity+and+permeability+of+crushed+and+damaged+rock+salt+during+compaction&ots=mxmKZOXh4M&sig=qf3AX5YV64vTb6wgqMq0TxTJuNY&redir_esc=y#v=onepage&q=Porosity%20and%20permeability.

[232] A. Rosenbleuth and N. Wiener, "The Role of Models in Science on JSTOR," *Philosophy of Science*, vol. 12, no. 4, pp. 316–321, 1945. [Online]. Available: https://www.jstor.org/stable/184253?seq=1.

[233] Nuclear Decommissioning Authority, "Geological Disposal: Framework for Application of Modelling in the Radioactive Waste Management Directorate (NDA Report no. NDA/RWMD/101)," NDA, NDA, UK, Tech. Rep. September, 2013, p. 113. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-framework-for-application-of-modelling-in-the-radioactive-waste-management-directorate/?download.

[234] U. Berner, "Project Opalinus Clay: Radionuclide Concentration Limits in the Near-Field of a Repository for Spent Fuel and Vitrified High-level Waste," Tech. Rep., 2002. [Online]. Available: https://www.nagra.ch/en/technical-report-02-10.

[235] M. Bradbury and B. Baeyens, "Far Field Sorption Data Bases for Performance Assessment of a High-Level Radioactive Waste Repository in an Undisturbed Opalinus Clay Host Rock," Tech. Rep., 2003. [Online]. Available: https://www.nagra.ch/en/technical-report-02-19.

[236] Nagra, "Synthese der Geowissenschaftlichen Untersuchungsergebnisse Entsorgungsnachweis für Abgebrannte Brennelemente, Verglaste Hochaktive Sowie Langlebige Mittelaktive Abfälle," Tech. Rep., 2002. [Online]. Available: https://www.nagra.ch/en/technischer-bericht-02-03.

[237] A. I. Marsh, L. G. Williams, and J. A. Lawrence, "A sensitivity study of the factors affecting the risks associated with the disposal of spent nuclear fuel in a geological disposal facility in a clay environment," *Progress in Nuclear Energy*, vol. 140, no. October, p. 103 910, 2021, ISSN: 01491970. DOI: 10.1016/j.pnucene.2021.103910. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0149197021002730.

[238] GoldSim Technology Group LLC, "Appendix B: Details of Pathway Computations," in *GoldSim: Contaminant Transport Module User Guide*, GoldSim Technology Group LLC, 2018. [Online]. Available: https://www.goldsim.com/Web/Customers/Education/Documentation/.

[239] International Atomic Energy Agency, *Safety Assessment Methodologies for Near Surface Disposal Facilities. Safety Assessment Methodologies for Near Surface Disposal Facilities. Results of a coordinated research project*, October. IAEA, Vienna, 2004, vol. 1, 2, p. 2. [Online]. Available: https://www.iaea.org/publications/6971/safety-assessment-methodologies-for-near-surface-disposal-facilities.

[240] Radioactive Waste Management Ltd., "Geological Disposal: Generic Post-closure Safety Assessment (NDA Report no. DSSC/321/01)," NDA, NDA, UK, Tech. Rep. December, 2016. [Online]. Available: http://scholar.google.com/scholar?hl=en&

btnG=Search&q=intitle:Geological+Disposal+Generic+Post-closure+Safety+Assessment#1.

[241] ——, "Geological Disposal: Disposal System Safety Case: Data Report (NDA Report no. DSSC/422/01)," NDA, UK, Tech. Rep. December, 2016, pp. 1–163. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-generic-disposal-system-safety-case-data-report/?download.

[242] T. Sullivan, "Waste Container and Waste Package Performance Modeling to Support Safety Assessment of Low and Intermediate-Level Radioactive Waste Disposal," Brookhaven National Laboratory, New York, Tech. Rep. BNL-74700-2005-IR W, 2004. [Online]. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.510.1496&rep=rep1&type=pdf.

[243] Y. Puzanov, "Safety and risk assessment of radioactive waste (RAW) and contaminated sites," in *Radioactive Waste Management and Contaminated Site Clean-Up - 1st Edition*, 2013, ch. 9, pp. 327–341. [Online]. Available: https://www.elsevier.com/books/radioactive-waste-management-and-contaminated-site-clean-up/lee/978-0-85709-435-3.

[244] Radioactive Waste Management Ltd., "Geological Disposal Generic Post-closure Performance Modelling (NDA Report no. NDA/RWM/138)," NDA, UK, Tech. Rep. December, 2016. [Online]. Available: https://rwm.nda.gov.uk/publication/nda-rwm-138-generic-post-closure-performance-modelling/?download.

[245] ——, "Geological Disposal: The 2013 Derived Inventory (NDA Report no. NDA/RWM/120)," RWM Ltd, NDA, UK, Tech. Rep., 2015. [Online]. Available: https://rwm.nda.gov.uk/publication/2013-derived-inventory/?download.

[246] International Commission on Radiological Protection, *ICRP Publication 107: Nuclear Decay Data for Dosimetric Calculations*, No. 3. Ottawa, Canada, 2008, vol. 38, pp. 35–96. [Online]. Available: http://journals.sagepub.com/doi/pdf/10.1177/ANIB_38_3.

[247] ——, "ICRP 2020 Annual Report," ICRP, Ottawa, Canada, Tech. Rep. ICRP Reference Number 4828-3163-0315, 2020, p. 7. [Online]. Available: https://www.sec.gov/ix?doc=/Archives/edgar/data/789019/000156459020034944/msft-10k_20200630.htm.

[248] A. Carter, M. Kelly, and L. Bailey, "Radioactive high level waste insight modelling for geological disposal facilities," *Physics and Chemistry of the Earth, Parts A/B/C*, vol. 64, pp. 1–11, 2013, ISSN: 1474-7065. DOI: 10.1016/J.PCE.2013.02.004. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1474706513000089#s0080.

[249] R. Walke, M. Thorne, and L. Limer, "RWMD Biosphere Assessment Model: Terrestrial Component," NDA RWMD, UK, Tech. Rep. 2, 2013. [Online]. Available: https://rwm.nda.gov.uk/publication/biosphere-assessment-model-terrestrial-component/?download.

[250] Radioactive Waste Management Ltd., "Geological Disposal: Biosphere Status Report (NDA Report no. DSSC/454/01)," RWM Ltd, NDA, UK, Tech. Rep. December, 2010. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-criticality-safety-status-report/.

[251] International Commission on Radiological Protection, *ICRP Publication 103: The 2007 Recommendations of the International Commission on Radiological Protection*, Volume 37. Ottawa, Canada, 2007, pp. 1–332, ISBN: 9780702055058. [Online]. Available: http://journals.sagepub.com/doi/pdf/10.1177/ANIB_37_2-4.

[252] Health Protection Agency, "Application of the 2007 Recommendations of the ICRP to the UK," Tech. Rep., 2009, p. 76. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/335097/RCE-12_for_website_v2.pdf.

[253] Radioactive Waste Management Ltd., "Geological Disposal: Waste packages and the assessment of their disposability (NDA Report no. DSSC/441/01)," RWM Ltd, NDA,

UK, Tech. Rep. February, 2016. [Online]. Available: https://rwm.nda.gov.uk/publication/geological-disposal-waste-packages-and-the-assessment-of-their-disposability/?download.

[254] ASSIST, "Integrated Project Team on Uranium: Phase 2 Post-closure Safety of DNLEU Disposal (Task ASS-4)," Tech. Rep., 2015. [Online]. Available: https://rwm.nda.gov.uk/publication/integrated-project-team-on-uranium-phase-2-post-closure-safety-of-dnleu-disposal/?download.

[255] SKB, "Data report for the safety assessment SR-Site," SKB, Stockholm, Tech. Rep. December, 2010. [Online]. Available: http://www.skb.se/upload/publications/pdf/TR-10-52.pdf.

[256] Nagra, "Far Field Sorption Data Bases for Performance Assessment of a High-Level Radioactive Waste Repository in an Undisturbed Opalinus Clay Host Rock," Nagra, Switzerland, Tech. Rep., 2003. [Online]. Available: www.psi.ch.

[257] United Kingdom Nirex Limited, "A Procedure for Data Elicitation in Support of Performance Assessments (Nirex Report N/132)," United Kingdom Nirex Ltd, Tech. Rep., 2006.

[258] A. Chambers and S. Williams, "The Basis for Cumulative Distribution Functions Used in the Groundwater Pathway Calculations of the Nirex Generic Post-closure Performance Assessment," Serco for United Kingdom Nirex Ltd, Tech. Rep. July, 2010. [Online]. Available: https://rwm.nda.gov.uk/publication/the-basis-for-cumulative-distribution-functions-used-in-the-groundwater-pathway-calculations-of-the-nirex-generic-post-closure-performance-assessment/?download.

[259] Environment Agency, "Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation," EA, UK, Tech. Rep., 2009. [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296504/geho0209bpjm-e-e.pdf.

[260] Health and Safety Executive (HSE), *Reducing risks, protecting people*. Sheffield, UK: HSE Books, 2001, pp. 1–74, ISBN: 0-7176-2151-0. [Online]. Available: http://linkinghub.elsevier.com/retrieve/pii/S0957582003710660.

[261] SKB, "Environmental Impact Statement: Interim storage, encapsulation and final disposal," SKB, Stockholm, Tech. Rep. March, 2011. [Online]. Available: http://www.skb.com/wp-content/uploads/2016/03/21014-MKB-ENG-webb-150dpi.pdf.

[262] International Atomic Energy Agency, *Joint Convention On The Safety Of Spent Fuel Management And On The Safety Of Radioactive Waste Management*, 1997. [Online]. Available: https://www.iaea.org/sites/default/files/infcirc546.pdf.

[263] ——, *Statute*, 1956. [Online]. Available: https://www.iaea.org/about/statute.

[264] C. Stoiber, A. Baer, N. Pelzer, and W. Tonhauser, *Handbook on Nuclear Law*. Vienna, Austria: IAEA, 2003. [Online]. Available: https://www-pub.iaea.org/mtcd/publications/pdf/pub1160_web.pdf.

[265] International Atomic Energy Agency, "Fundamental Safety Principles (Safety Fundamentals No. SF-1)," Tech. Rep., 2011, pp. 3–7. [Online]. Available: http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1273_web.pdf.

[266] European Union, *Council Directive 2011/70/EURATOM of 19 July 2011 establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste*, 2011. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0070&from=EN.

[267] "Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment (L26/1)," 2011. [Online]. Available: https://www.legislation.gov.uk/eudr/2011/92/pdfs/eudr_20110092_adopted_en.pdf.

[268] Western European Nuclear Regulators Association Working Group on Waste and Decommissioning, "Radioactive Waste Disposal Facilities Safety Reference Levels," WENRA WGWD, Tech. Rep. December, 2014. [Online]. Available: https://www.

wenra.eu/sites/default/files/workinggroups/wgwd/srl_disposal_final_version_2014_12_22.pdf.

[269] Office for Nuclear Regulation, "Management of Radioactive Material and Radioactive Waste on Nuclear Licensed Sites (NS-TAST-GD-24)," ONR, ONR, UK, Tech. Rep., 2019, pp. 1–27. [Online]. Available: https://www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-024.pdf.

[270] ——, "Implementing ONR's strategy for licensing a future Geological Disposal Facility: Applicability of licensing guidance and current Licence Conditions to a future Geological Disposal Facility," ONR, UK, Tech. Rep. July, 2016. [Online]. Available: https://www.onr.org.uk/pars/2016/sdfw-16-007.pdf.

[271] Organisation for Economic Co-ordination and Development (OECD), *Convention on Third Party Liability in the Field of Nuclear Energy*, 1960. [Online]. Available: https://www.oecd-nea.org/jcms/pl_31788/paris-convention-full-text.

[272] ——, *Convention of 31 January 1963 Supplementary to the Paris Convention of 29 July 1960 (Brussels Supplementary Convention)*, 1963. [Online]. Available: https://legalinstruments.oecd.org/public/doc/197/197.en.pdf.

[273] "Protocol to Amend the Convention on Third Part Liability in the Field of Nuclear Energy of 29 July 1960, As Amended by the Additional Protocol of 28 January 1964 and by the Protocol of 16 November 1982," Tech. Rep., 2004. [Online]. Available: https://www.oecd-nea.org/jcms/pl_20382/2004-protocol-to-amend-the-paris-convention.

[274] UK Parliament, *Nuclear Installations (Liability for Damage) Order 2016 (SI no. 2016/562)*, 2016. [Online]. Available: http://www.legislation.gov.uk/uksi/2016/562/pdfs/uksiem_20160562_en.pdf.

[275] ——, *Nuclear Installations (Prescribed Sites and Transport) Regulations 2018 (SI no. 2018/42)*, 2018. [Online]. Available: https://www.legislation.gov.uk/uksi/2018/42/made.

[276] ——, *Nuclear Safeguards Act 2000 (2000 Chapter 5)*, 2000. [Online]. Available: http://www.legislation.gov.uk/ukpga/2000/5/pdfs/ukpga_20000005_en.pdf.

[277] International Atomic Energy Agency, *Protocol Additional to the Agreement between the United Kingdom of Great Britain and Northern Ireland and the International Atomic Energy Agency for the Application of Safeguards in the United Kingdom of Great Britain and Northern Ireland in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons (NFCIRC/951/Add.1)*, 2021. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/754614/MS_12.2018_VOA_Protocol.pdf.

[278] Ministry of Trade and Industry (Finland), *Nuclear Energy Act (990/1987 amended up to 342/2008)*, 1987. [Online]. Available: http://www.finlex.fi/en/laki/kaannokset/1987/en19870990.pdf.

[279] Radiation and Nuclear Safety Authority (STUK), *Radiation and Nuclear Safety Authority Regulation on the Safety of Disposal of Nuclear Waste (Y/4/2018)*, 2018. [Online]. Available: https://www.stuklex.fi/en/maarays/stuk-y-4-2018#L7.

[280] Ministry of Trade and Industry (Finland), *Radiation Protection Act (859/2018)*, 2018. [Online]. Available: http://dx.doi.org/10.1053/j.gastro.2014.05.023%0Ahttps://doi.org/10.1016/j.gie.2018.04.013%0Ahttp://www.ncbi.nlm.nih.gov/pubmed/29451164%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC5838726%250Ahttp://dx.doi.org/10.1016/j.gie.2013.07.022.

[281] Finnish Parliament, *Nuclear Liability Act (No. 484/1972)*, 1972. [Online]. Available: https://www.stuklex.fi/en/19720484e.pdf.

[282] Radiation and Nuclear Safety Authority (STUK), "Guide YVL D.5: Disposal of Nuclear Waste," STUK, Helsinki, Tech. Rep., 2018. [Online]. Available: https://www.finlex.fi/data/normit/41417/YVL_D.5e.pdf.

[283] ——, "Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management: 6th Finnish National Report as referred to in

Article 32 of the Convention," STUK, Helsinki, Tech. Rep. 8, 2017, pp. 640–640. DOI: 10.3327/jaesjb.51.8{_}640. [Online]. Available: https://www.iaea.org/sites/default/files/national_report_of_finland_for_the_6th_review_meeting_-_english.pdf.

[284] Government of Sweden, *The Act on Nuclear Activities (1984:3)*, 1984. [Online]. Available: https://www.iaea.org/sites/default/files/national_report_of_finland_for_the_6th_review_meeting_-_english.pdf.

[285] ——, *Ordinance with Instructions for the Swedish Radiation Safety Authority (2008:452)*, 2008. [Online]. Available: https://www.stralsakerhetsmyndigheten.se/contentassets/54ebbfc0517a431b88ee759a32e43279/ordinance-with-instructions-for-the-swedish-radiation-safety-authority-2008452.pdf.

[286] ——, *Radiation Protection Act (2018:396)*, 2018. [Online]. Available: http://www.notisum.se/rnp/document/?id=20180396.

[287] ——, *The Environmental Code*, 1998. [Online]. Available: http://www.government.se/49b73c/contentassets/be5e4d4ebdb4499f8d6365720ae68724/the-swedish-environmental-code-ds-200061.

[288] Swedish Radiation Safety Authority (SSM), *Swedish Radiation Safety Authority Regulatory Code (SSMFS 2008:21)- The Swedish Radiation Safety Authority's regulations and general advice concerning safety in connection with the disposal of nuclear material and nuclear waste*, 2008. [Online]. Available: https://www.stralsakerhetsmyndigheten.se/contentassets/d138388c47964b8a951ec8ca919ac485/ssmfs-200821-the-swedish-radiation-safety-authoritys-regulations-concerning-safety-in-connection-with-the-disposal-of-nuclear-material-and-nuclear-waste.

[289] Swedish Radiation Safety Authority, *Swedish Radiation Safety Authority Regulatory Code (SSMFS 2008:37)-The Swedish Radiation Safety Authority's Regulations and General Advice Concerning the Protection of Human Health and the Environment in Connection with the Final Management of Spent Nucle*, 2008. [Online]. Available:

https://www.stralsakerhetsmyndigheten.se/contentassets/d138388c47964b8a951ec8ca9
ssmfs-200821-the-swedish-radiation-safety-authoritys-regulations-
concerning-safety-in-connection-with-the-disposal-of-nuclear-material-
and-nuclear-waste.

[290] Ministry of the Environment Sweden, *Sweden's Seventh National Report under the Joint Convention on the safety of spent fuel and on the safety of radioactive waste management. Ds 2020 : Sweden's Implementation of the obligations of the Joint Convention.* 2020, ISBN: 9789138250990. [Online]. Available: https://www.regeringen.se/4aac1f/contentassets/ace68a7f79ec46bea20dffc76bfbeb85/swedens-seventh-national-report-under-the-joint-convention-on-the-safety-of-spent-fuel-management-and-on-the-safety-of-radioactive-waste-management-ds-2020-21.

[291] Swedish Radiation Safety Authority (SSM), *Swedish Radiation Safety Authority Regulatory Code (SSMFS 2008:38)- The Radiation Safety Authority's regulations on archiving at nuclear facilities*, 2008. [Online]. Available: https://www.stralsakerhetsmyndighet
se/publikationer/foreskrifter/ssmfs-2008/ssmfs-200838/.

[292] Swedish Radiation Safety Authority, *Swedish Radiation Safety Authority Regulatory Code (SSMFS 2008:01)- The Swedish Radiation Safety Authority's Regulations and General Advice concerning Safety in Nuclear Facilities*, 2008. [Online]. Available: https://www.stralsakerhetsmyndigheten.se/contentassets/e8ba282f8ef0461ca392137c9495f46
ssmfs-20081-the-swedish-radiation-safety-authoritys-regulations-
concerning-safety-in-nuclear-facilities.

[293] *Decree n° 2007-830 of 11 May 2007 relating to the nomenclature of basic nuclear installations.* 2007. [Online]. Available: https://www.legifrance.gouv.fr/loda/id/JORFTEXT000000428384/.

[294] Nuclear Safety Authority (ASN), *Act No. 2006-686 on Transparency and Security in the Nuclear Field Nuclear Safety Authority*, 2006. [Online]. Available: https://www.french-nuclear-safety.fr/content/download/85450/594666?version=2.

[295] *Order of 7 February 2012 setting the general rules relative to basic nuclear installations (JORF No. 0033 of 8 February 2012, Text No. 12)*, 2012. [Online]. Available: https://www.french-nuclear-safety.fr/content/download/85452/594681?version=1.

[296] *Decree n° 2007-1557 of 2 November 2007 relating to basic nuclear installations and the control, in terms of nuclear safety, of the transport of radioactive substances.* 2007. [Online]. Available: http://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000000469544&dateTexte=20080718&fastPos=1&fastReqId=1021957698&oldAction=rechTexte.

[297] Parliamentary Office for the Evaluation of Scientific and Technological Choices, *2006 Programme Act on the Sustainable Management of Radioactive Materials and Wastes*, 2006. [Online]. Available: https://www.french-nuclear-safety.fr/content/download/85454/594696?version=1.

[298] *Law n° 68-943 of October 30, 1968 relating to civil liability in the field of nuclear energy.* 1968. [Online]. Available: https://www.legifrance.gouv.fr/affichTexte.do?cidTexte=JORFTEXT000000501105&categorieLien=cid#:~:text=Dans%20les%20r%C3%A9sum%C3%A9s-,Loi%20n%C2%B0%2068-943%20du%2030%20octobre%201968%20relative,domaine%20de%20l'%C3%A9nergie%20nucl%C3%A9aire.&text=Le%20montant%20maximum%20de%20la,pour%20un%20m%C3%AAme%20accident%20nucl%C3%A9aire.

[299] *Public health code (Article L1453-1)*, 2011. [Online]. Available: https://www.legifrance.gouv.fr/codes/article_lc/LEGIARTI000038888435/.

[300] Deutscher Bundestag, *Basic Law for the Federal Republic of Germany (Classification no. 100-1)*, 1949. [Online]. Available: https://www.btg-bestellservice.de/pdf/80201000.pdf.

[301] The Federal Office for Radiation Protection (Bundesamt für Strahlenschutz – BfS), *Act on the Peaceful Utilisation of Atomic Energy and the Protection against its Hazards (Atomic Energy Act)*, 1959. [Online]. Available: https://www.base.bund.de/SharedDocs/Downloads/BASE/EN/hns/a1-english/A1-07-16-AtG.pdf?__blob=publicationFile&v=2.

[302] Bundesamt für Strahlenschutz, *Ordinance on Protection against the Harmful Effects of Ionising Radiation – Radiation Protection Ordinance (StrlSchV)*, 2001. [Online]. Available: https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Gesetze/strlschv_en_bf.pdf.

[303] *Act on the Protection against the Harmful Effect of Ionising Radiation (Strahlenschutzgesetz - StrlSchG)*, 2018. [Online]. Available: http://www.gesetze-im-internet.de/strlschg/.

[304] *Ordinance on the Procedure for Licensing of Installations under § 7 of the Atomic Energy Act*, 1977. [Online]. Available: https://www.base.bund.de/SharedDocs/Downloads/BASE/DE/rsh/a1-englisch/A1-12-06.pdf?__blob=publicationFile&v=1.

[305] *Ordinance on the Shipment of Radioactive Waste or Spent Fuel*, 2009. [Online]. Available: https://www.base.bund.de/SharedDocs/Downloads/BASE/DE/rsh/a1-englisch/A1-12-06.pdf?__blob=publicationFile&v=1.

[306] *Act on the Search and Selection of a Site for a Repository for Heat-Generating Radioactive Waste and for the Amendment of Other Laws (Standortauswahlgesetz - StandAG)*, 2017. [Online]. Available: http://www.gesetze-im-internet.de/standag_2017/index.html.

[307] *Law on the establishment of a Federal Office for the Safety of Nuclear Waste Management (BfkEG)*, 2013. [Online]. Available: https://www.gesetze-im-internet.de/bfkeg/__1.html.

[308] B. Federal Ministry for the Environment Nature Conservation and N. Safety, "Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management: Report of the Federal Republic of Germany for the Sixth Review Meeting in May 2018," Tech. Rep., 2018.

[309] ——, *Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste As at 30 September 2010 (BMU 10)*, 2010. [Online]. Available: https://www.bmuv.de/domainswitch/fileadmin/bmu-import/files/english/pdf/application/pdf/sicherheitsanforderungen_endlagerung_en_bf.pdf.

[310] The Federal Assembly of the Swiss Confederation, *Nuclear Energy Act (NEA) (732.1)*, 2003. [Online]. Available: https://www.fedlex.admin.ch/eli/cc/2004/723/en.

[311] ——, *Radiological Protection Act (RPA)*, 2017. [Online]. Available: https://www.fedlex.admin.ch/eli/cc/1994/1933_1933_1933/en.

[312] The Swiss Federal Council, *Radiological Protection Ordinance (RPO) (814.501)*, 2017. [Online]. Available: https://www.fedlex.admin.ch/eli/cc/2017/502/en.

[313] The Federal Assembly of the Swiss Confederation, *Federal Act on the Protection of the Environment (Environmental Protection Act, EPA) (814.01)*, 1983. [Online]. Available: https://www.fedlex.admin.ch/eli/cc/1984/1122_1122_1122/en.

[314] ——, *Swiss Federal Nuclear Safety Inspectorate Act (732.2)*, 2007. [Online]. Available: https://www.fedlex.admin.ch/eli/cc/2007/775/de.

[315] The Swiss Federal Council, *Nuclear Energy Ordinance (NEO) of 10 December 2004 (732.11)*, 2004. [Online]. Available: https://www.admin.ch/opc/en/classified-compilation/20042217/201810160000/732.11.pdf.

[316] Japan Atomic Energy Commission (JAEC), *The Atomic Energy Basic Law (Act No. 186 of December 19, 1955)*, 1955. [Online]. Available: http://www.aec.go.jp/jicst/NC/about/kettei/170605.pdf.

[317] *Act for Establishment of the Nuclear Regulation Authority (Act No. 47 of June 27, 2012)*, 2012. [Online]. Available: http://www.nsr.go.jp/data/000067231.pdf.

[318] *Act on the Regulation of Nuclear Source Material , Nuclear Fuel Material and Reactors (Act No. 166 of June 10, 1957)*, 1957. [Online]. Available: https://www.oecd-nea.org/upload/docs/application/pdf/2020-03/act_on_the_regulation_of_nuclear_source_material_nuclear_fuel_material_and_reactors.pdf.

[319] *Act on Prevention of Radiation Hazards due to Radioisotopes, etc. (Act No. 167 of June 10, 1957)*, 2014. [Online]. Available: https://www.nsr.go.jp/data/000182245.pdf.

[320] "National Report of JAPAN for the Sixth Review Meeting- Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management," Tech. Rep. October, 2017. [Online]. Available: https://www.iaea.org/sites/default/files/national_report_of_japan_for_the_6th_review_meeting_-_english.pdf.

[321] *Act on Special Measures Concerning Nuclear Emergency Preparedness Act No. 156 of December 17, 1999)*, 1999. [Online]. Available: http://www.cas.go.jp/jp/seisaku/hourei/data/ASMCNEP.pdf.

[322] G. T. Rubin, *Escape From Yucca Mountain: Biden Administration Promises Progress on Nuclear Waste*, 2021. [Online]. Available: https://www.wsj.com/articles/escape-from-yucca-mountain-biden-administration-promises-progress-on-nuclear-waste-11620984602.

[323] *Atomic Energy Act of 1954 (P.L. 83-703, 68 Stat. 919)*, 1954. [Online]. Available: https://www.nrc.gov/docs/ML1327/ML13274A489.pdf#page=241.

[324] *Energy Reorganization Act of 1974 (P.L. 93-438, 88 STAT. 1233)*, 1974. [Online]. Available: https://www.nrc.gov/docs/ML1327/ML13274A489.pdf#page=241.

[325] US Department of Energy, *The Nuclear Waste Policy Act of 1982 (96 STAT 2201)*, 1982. [Online]. Available: http://www.epw.senate.gov/nepa69.pdf.

[326] US Government, *Title 10: Energy- Parts 1 to 50*, 2020. DOI: 10.14724/03.10. [Online]. Available: https://www.govinfo.gov/content/pkg/CFR-2020-title10-vol1/pdf/CFR-2020-title10-vol1.pdf.

[327] ——, *Title 10: Energy- Parts 51 to 199*, 2020. DOI: 10.14724/03.10. [Online]. Available: https://www.govinfo.gov/content/pkg/CFR-2020-title10-vol2/pdf/CFR-2020-title10-vol2.pdf.

[328] *Energy Policy Act of 1992 (106 STAT 2776)*, 1992. [Online]. Available: https://www.congress.gov/102/statute/STATUTE-106/STATUTE-106-Pg2776.pdf.

[329] Nuclear Regulatory Commission, *Agreement State Program*, 2021. [Online]. Available: https://www.nrc.gov/about-nrc/state-tribal/agreement-states.html.

[330] *Department of Energy Organization Act (91 Stat 567)*, 1977. [Online]. Available: https://www.ferc.gov/media/department-energy-organization-act.

[331] U.S. Department of Energy, "United States of America Sixth National Report for the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management," Tech. Rep., 2017. [Online]. Available: https://www.energy.gov/em/downloads/sixth-national-report-joint-convention-safety-spent-fuel-management-and-safety.

[332] L. G. Williams, "Overview of International Nuclear Safety Regulation and Licensing," in *Encyclopedia of Nuclear Energy*, Elsevier Inc., 2021, pp. 188–206, ISBN: 9780124095489. DOI: 10.1016/b978-0-12-409548-9.12380-2. [Online]. Available: http://dx.doi.org/10.1016/B978-0-12-409548-9.12380-2.

[333] UK Parliament, *Infrastructure Planning (Environmental Impact Assessment) Regulations 2017 (SI no. 2017/572)*, 2017. [Online]. Available: https://www.legislation.gov.uk/uksi/2017/572/contents/made.

[334] Welsh Government, *Town and Country Planning (Environmental Impact Assessment) (Wales) Regulations 2017 (SI no. 2017/567, W. 2017/136)*, 2017. [Online]. Available: https://www.legislation.gov.uk/wsi/2017/567/made.

[335] UK Parliament, *Energy Act 2013 (2013 Chapter 32)*, 2013. [Online]. Available: https://www.legislation.gov.uk/id/ukpga/2013/32.

[336] ——, *Nuclear Installations Regulations 1971 (SI no. 1971/381)*, 1971. [Online]. Available: http://www.legislation.gov.uk/uksi/1971/381/pdfs/uksi_19710381_en.pdf.

[337] Office for Nuclear Regulation, "Consultation on ONR's revised interpretation of ' bulk quantities ' in the context of licensing nuclear installations for storage and disposal of radioactive matter," ONR, UK, Tech. Rep. November, 2020. [Online]. Available: https://www.onr.org.uk/consultations/2020/bulk-quantities/bulk-quantities-consultation.pdf.

[338] UK Parliament, *Health and Safety at Work etc Act 1974 (1974 Chapter 37)*, 1974. [Online]. Available: https://www.legislation.gov.uk/ukpga/1974/37.

[339] ——, *Ionising Radiations Regulations 2017 (SI no. 2017/1075)*, 2017. [Online]. Available: https://www.legislation.gov.uk/uksi/2017/1075/contents/made.

[340] ——, *Radiation (Emergency Preparedness and Public Information) Regulations 2019 (SI no. 2019/703)*, 2019. [Online]. Available: https://www.legislation.gov.uk/nisr/2019/185/made.

[341] ——, *Nuclear Industries Security Regulations 2003 (SI no. 2003/403)*, 2003. [Online]. Available: https://www.legislation.gov.uk/uksi/2003/403/made.

[342] ——, *Nuclear Safeguards Act 2018 (2018 Chapter 15)*, 2018. [Online]. Available: https://researchbriefings.files.parliament.uk/documents/CBP-8107/CBP-8107.pdf.

[343] ——, *Nuclear Safeguards (EU Exit) Regulations 2019 (SI no. 2019/196)*, 2019. [Online]. Available: https://www.legislation.gov.uk/uksi/2019/196/contents/made.

[344] ——, *Planning Act 2008 (2008 Chapter 29)*, 2008. [Online]. Available: http://www.legislation.gov.uk/ukpga/2008/29/pdfs/ukpga_20080029_en.pdf%20https://www.legislation.gov.uk/ukpga/2008/29/pdfs/ukpga_20080029_en.pdf.

[345] Welsh Government, *Natural Resources Body for Wales (Establishment) Order 2012 (SI no. 2012/1903, W. 2012/230)*, 2012. [Online]. Available: https://www.legislation.gov.uk/wsi/2012/1903/made.

[346] Office for Nuclear Regulation, "ONR - Licence Condition Handbook," Tech. Rep., 2017. [Online]. Available: http://www.onr.org.uk/documents/licence-condition-handbook.pdf.

[347] ——, "ONR Guide- The Purpose and Use of Permissioning," Tech. Rep., 2021. [Online]. Available: http://www.onr.org.uk/operational/assessment/ns-per-gd-001.pdf.

[348] ——, "ONR GUIDE: PROCUREMENT AND INTELLIGENT CUSTOMER CAPABILITY," Tech. Rep., 2020, p. 4. [Online]. Available: https://www.onr.org.uk/operational/tech_asst_guides/cns-tast-gd-4.1.pdf.

[349] ——, "Safety Assessment Principles For Nuclear Facilities," ONR, UK, Tech. Rep. 2014 Edition, Revision 1, 2020. [Online]. Available: https://www.onr.org.uk/saps/saps2014.pdf.

[350] ——, "Security Assessment Principles for the Civil Nuclear Industry," ONR, UK, Tech. Rep., 2017. [Online]. Available: https://www.onr.org.uk/syaps/security-assessment-principles-2017.pdf.

[351] UK Parliament, *Nuclear Safeguards (Notification) Regulations 2004 (SI no. 2004/1255)*, 2004. [Online]. Available: https://www.legislation.gov.uk/uksi/2004/1255/made.

[352] Department for Business Energy & Industrial Strategy, "The United Kingdom's Sixth National Report on Compliance with the Obligations of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.," Office for Nuclear Regulation, BEIS, London, UK, Tech. Rep. October, 2017. [Online]. Available: https://assets.publishing.service.gov.uk/government/

uploads/system/uploads/attachment_data/file/672640/20171020_-_UK_Sixth_National_Report_to_the_Joint_Convention.pdf.

[353] Office for Nuclear Regulation, "ONR Guide- LC2: Marking the Site Boundary," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-002.pdf.

[354] ——, "ONR Guide- LC3: Control of Property Transactions Document," Tech. Rep., 2018. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-003.pdf.

[355] ——, "ONR Guide- LC4: Restrictions on Nuclear Matter on the Site Document," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-004.pdf.

[356] ——, "ONR Guide- LC5: Consignment of Nuclear Matter," Tech. Rep., 2020. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-005.pdf.

[357] ——, "ONR Guide- LC6: Documents, records, authorities and certificates," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-006.pdf.

[358] ——, "ONR Guide- LC7: Incidents on the Site Document," Tech. Rep., 2020. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-007.pdf.

[359] ——, "ONR Guide- LC8: Warning Notices," Tech. Rep., 2018. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-008.pdf.

[360] ——, "ONR Guide- LC9: Instructions to Persons on the Site," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-009.pdf.

[361] ——, "ONR Guide- LC10: Training," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-010.pdf.

[362] ——, "ONR Guide- LC11: On-site Emergency Arrangements," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-011.pdf.

[363] ——, "ONR Guide- LC12: Duly authorised and other suitably qualified and experienced persons," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-012.pdf.

[364] ——, "ONR Guide- LC13: Nuclear Safety Committee," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-013.pdf.

[365] ——, "ONR Guide- LC14: Safety Documentation," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-014.pdf.

[366] ——, "ONR Guide- LC15: Periodic Review," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-015.pdf.

[367] ——, "ONR Guide- LC16: Site Plans, Designs and Specifications," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-016.pdf.

[368] ——, "ONR Guide- LC17: Management Systems," Tech. Rep., 2017. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-017.pdf.

[369] Her Majesty's Stationery Office, "Sizewell B Inquiry," Tech. Rep., 1987. [Online]. Available: https://discovery.nationalarchives.gov.uk/details/r/C7081.

[370] Office for Nuclear Regulation, "ONR Guide- LC18: Radiological Protection," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-018.pdf.

[371] ——, "ONR Guide- LC19: Construction or Installation of New Plant," Tech. Rep., 2018. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-019.pdf.

[372] ——, "ONR Guide- LC20: Modification to Design of Plant under Construction," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-020.pdf.

[373] ——, "ONR Guide- LC21: Commissioning," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-021.pdf.

[374] ——, "ONR Guide- LC22: Modification or experiment on existing plant," Tech. Rep., 2021. [Online]. Available: http://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-022.pdf.

[375] ——, "ONR Guide- LC23: Operating Rules," Tech. Rep., 2021, pp. 1–30. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-023.pdf.

[376] ——, "ONR Guide- LC24: Operating Instructions," Tech. Rep., 2019. [Online]. Available: http://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-024.pdf.

[377] ——, "ONR Guide- LC25: Operational Records," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-025.pdf.

[378] International Atomic Energy Agency, "IAEA Safety Standards: Disposal of Radioactive Waste- Specific Safety Requirements (No. SSR-5)," Tech. Rep., 2011, p. 3. [Online]. Available: https://www-pub.iaea.org/mtcd/publications/pdf/pub1449_web.pdf.

[379] Office for Nuclear Regulation, "ONR Guide- LC26: Control and Supervision of Operations," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-026.pdf.

[380] ——, "ONR Guide- LC27: Safety Mechanisms, Devices and Circuits," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-027.pdf.

[381] ——, "ONR Guide- LC28: Examination, Inspection, Maintenance and Testing," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-028.pdf.

[382] ——, "ONR Guide- LC29: Duty to Carry out Tests, Inspections and Examinations," Tech. Rep., 2018. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-029.pdf.

[383] ——, "ONR Guide- LC30: Periodic Shutdown," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-030.pdf.

[384] ——, "ONR Guide- LC32: Accumulation of Radioactive Waste," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-032.pdf.

[385] ——, "ONR Guide- LC33: Disposal of Radioactive Waste," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-033.pdf.

[386] ——, "ONR Guide- LC34: Leakage and Escape of Radioactive Material and Radioactive Waste," Tech. Rep., 2019. [Online]. Available: www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-021.pdf.

[387] ——, "ONR Guide- LC35: Decommissioning," Tech. Rep., 2019. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-035.pdf.

[388] ——, "ONR Guide- LC36: Organisational Capability," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/operational/tech_insp_guides/ns-insp-gd-036.pdf.

[389] Environment Agency, Scottish Environment Protection Agency, and Natural Resources Wales, "Management of radioactive waste from decommissioning of nuclear sites: Guidance on Requirements for Release from Radioactive Substances Regulation," Tech. Rep., 2018. [Online]. Available: https://www.sepa.org.uk/media/365893/2018-07-17-grr-publication-v1-0.pdf.

[390] Environment Agency, *Permit with introductory note (Low Level Waste Repository Permit number EPR/YP3293SA)*, 2010. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/471947/LLWR_permit.pdf.

[391] UK Cabinet Office, "Nuclear Industries Security Regulations 2003: Guidance," Tech. Rep. Version 4.1, 2015. [Online]. Available: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/365957/Nuclear_Industries_Security_Regulations.pdf.

[392] UK Parliament, *Anti-terrorism, Crime and Security Act 2001 (2001 Chapter 24)*, 2001. [Online]. Available: https://www.legislation.gov.uk/ukpga/2001/24.

[393] ——, *Energy Act 2004 (2004 Chapter 20)*, 2004. [Online]. Available: https://www.legislation.gov.uk/ukpga/2004/20/contents#openingWholeMod.

[394] *Treaty on the Non-Proliferation of Nuclear Weapons (NPT)*, 1968. [Online]. Available: https://www.un.org/disarmament/wmd/nuclear/npt/text.

[395] International Atomic Energy Agency, "Technological Implications of International Safeguards for Geological Disposal of Spent Fuel and Radioactive Waste (IAEA Nuclear Series No. NW-T-1.21)," IAEA, Vienna, Tech. Rep., 2010. [Online]. Available: http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1414_web.pdf.

[396] ——, "Geological Disposal of Radioactive Waste: Technological Implications of Retrievability," Tech. Rep., 2006. [Online]. Available: http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1378_web.pdf.

[397] Office for Nuclear Regulation and Environment Agency, *Memorandum Of Understanding Between The Office For Nuclear Regulation And The Environment Agency On Matters Of Mutual Interest In England*, 2015. [Online]. Available: https://www.onr.org.uk/documents/2015/mou-onr-ea-180815.pdf.

[398] Office for Nuclear Regulation and Scottish ENvironment Protection Agency, *Memorandum Of Understanding Between The Office For Nuclear Regulation And The Scottish Environment Protection Agency (SEPA) On Matters Of Mutual Interest In Scotland*, 2019. [Online]. Available: https://www.onr.org.uk/documents/2019/mou-onr-sepa.pdf.

[399] Office for Nuclear Regulation and Natural Resources Wales, "Memorandum Of Understanding Between The Office For Nuclear Regulation And The Natural Resources Body for Wales Agency On Matters Of Mutual Interest In Wales," Tech. Rep., 2014. [Online]. Available: https://www.onr.org.uk/documents/2015/nrw-mou.pdf.

[400] Office for Nuclear Regulation, "Interpretation of 'bulk quantities' in relation to the storage and disposal of radioactive matter," Tech. Rep., 2021. [Online]. Available: https://www.onr.org.uk/consultations/2020/bulk-quantities/bulk-quantities-position-statement.pdf.

[401] E. Pentti and E. Heikkinen, "TR Usability of Olkiluoto Monitoring Programme for implementing nuclear safeguards (STUK-TR 28)," Tech. Rep. [Online]. Available: https://core.ac.uk/download/pdf/141500054.pdf.

Appendix A- Underlying Equations (Chapter 5)

Radionuclide mass transfer release rate

The release rate of radionuclides from spent fuel pellets into groundwater is described by the congruence of two processes, instant release and dissolution, represented by:

$$R_i = f_{IRF}^i M_i(t-\in)\delta(t-T) + kM_i(t)H(t-T) \quad (1A)$$

In this description, f_{IRF} represents the fraction of radionuclide i contained within the instant release fraction of the inventory, M_i is the total mass of radionuclide i initially bound to the wasteform matrix (pellet), t the time and T the time of canister failure. Each of the two terms correspond to values input within the source inventory settings.

Diffusion in GoldSim

The way diffusion is modelled in GoldSim, through well-mixed compartments, can be represented by a generalised form of the discretised diffusion equation:

$$V\frac{dC_i}{dt} = \frac{DA}{\Delta x}(C_{i+1} - C_i) - \frac{DA}{\Delta x}(C_i - C_{i-1}) \quad (2A)$$

Where V represents the volume of the compartment, C_i the concentration of radionuclides at a point i along the path, and DA/Δx the rate constant with which radionuclides are exchanged between points along the path.

Diffusive mass flow rate

Within GoldSim, the diffusive mass flow rate (or diffusive flux) across the boundary is represented by:

$$\left(F_{D,i}\right) = Diffusive\ Conductance\ (D) \times Concentration\ Difference\ (C_n - C_{n+1}) \quad (3A)$$

Where the concentration difference represents the variance in the concentration of a radionuclide within the reference fluid (water) between the two compartments and the diffusive conductance is a function referring to the properties of the radionuclides, groundwater and the geometry of the diffusive pathway.

Transport equation for buffer compartments

The mass balance ("transport") equation for a compartment in the buffer, with volume Vn and concentration of radionuclide i, in compartment n, $C_n{}^i$ can be written as:

$$\alpha_{B,i}V_{B,n}\frac{dC_n^i}{dt} = D_{Bn.n-1}\left(C_{n-1}^i - C_n^i\right) - D_{B,n}\cdot C_n^i - \lambda_i\alpha_{B,i}V_nC_n^i + \lambda_{i-1}\alpha_{B,i-1}V_nC_n^{i-1} \quad (4A)$$

Where α represents a capacity factor for radionuclides in the buffer, term 1 of the equation corresponds to diffusive flux into the compartment, term 2 diffusion losses, the third term represents the evolution of concentration due to radioactive decay and the final term due to ingrowth of radionuclides.

At t=0 yr, radionuclide concentration is proportional to the mass present in the compartment and solubility limits.

Transport equation in the overlying geology

In modelling advection through the overlying chalk as migration through a porous medium the transport equation takes the form:

$$R^i\frac{\partial C_P^i}{\partial t} = -\frac{q}{\varphi_m}\frac{\partial C_P^i}{\partial x} + \frac{q\alpha}{\varphi_m}\frac{\partial^2 C_P^i}{\partial x^2} - R^iC_P^i\lambda^i + R^{i-1}C_P^{i-1}\lambda^{i-1} \quad (5A)$$

Where $q\alpha/\phi_m$ represents the longitudinal dispersion coefficient in the porous medium. Here q ($m.yr^{-1}$) R_i retardation by the overlying chalk, via radionuclide sorption, ϕ_m the porosity of the porous medium, α (m) the dispersion length and C_p^i corresponds to the concentration in the porous chalk of radionuclide, i. The third and fourth terms represent radioactive decay and ingrowth of radionuclides.

Mass transfer conservation

It is assumed that all mass transferred from a single cell (e.g. cell 1 in the porous medium P1) is equal to the mass entering the adjacent downstream cell (e.g. cell 2):

$$\frac{q}{\varphi_m}\frac{\partial C_{P1}^i}{\partial x} - \frac{q\alpha}{\varphi_m}\frac{\partial^2 C_{P1}^i}{\partial x^2} = \frac{q}{\varphi_m}\frac{\partial C_{P2}^i}{\partial x} - \frac{q\alpha}{\varphi_m}\frac{\partial^2 C_{P2}^i}{\partial x^2} \quad (6A)$$

Mass flux to the biosphere

The mass flux to the biosphere is calculated by:

$$Mass\ Flux\ to\ Biosphere\ (F_{OUT}) = A\left(qC_P^i - \frac{q\alpha}{\varphi_m}\frac{\partial C_P^i}{\partial x}\right)\ at\ x = L_P \quad (7A)$$

Where A is the radionuclide flow through cross-section (m^2) and L_p the flow pathlength through the geosphere.

Activity flux to the biosphere

The "mass flux" calculated in equation 7A is converted to an activity flux in the GoldSim model by:

$$Activity\ Flux\ (F_j) = F_{Out}(g.yr^{-1}) \times S_i^A(Bq.g^{-1}) \quad (8A)$$

Where $S_i{}^A$ corresponds to the specific activity of each radionuclide, i.

Biosphere dose conversion factors

The annual radiological risk to PEGs is calculated by applying biosphere conversion factors to the resultant biosphere dose. The biosphere factors (H_{PEG}) are generated utilising a variant of 9A, depending on the groundwater pathway(s) assumed:

$$H_{PEG} = \frac{H_{ND}}{A} + \frac{H_{well}}{F} \quad (9A)$$

Where H_{ND} corresponds to the effective dose rate in unit flux of groundwater for the natural discharge pathway and H_{well} the equivalent for the well pathway, A the discharge area and F the flow rate in the well aquifer.

Effective dose to PEGs

The final step prior to calculation of the annual radiological risk was the conversion of activity flux to an effective dose:

$$D_i\ (Sv.yr^{-1}) = F_j(Bq.yr^{-1}) \times H_{PEG}\ (Sv.Bq^{-1}) \quad (10A)$$

By multiplying the flux of activity, F_j, by the biosphere factor H_{PEG}.

Annual radiological risk (R_i):

The annual radiological risk to a potentially exposed group (PEG) member was generated from the effective dose by multiplication with risk factor, r as:

$$R_i(yr^{-1}) = D_i \times r \quad (11A)$$

Appendix B - Input Data (Chapter 5)

Inventory

The AGR SNF inventory for disposal was model was in the model by the mass (g) of individual radionuclides:

$$m = \frac{\lambda N}{a} \quad (1B)$$

where λ represents the decay constant of the isotope and N the number of atoms respectively, cumulatively representing the activity of the radionuclide, and a which represents the specific activity of the isotope.

Table B.1: Radionuclide inventory by mass.

Isotope	Mass/ g	Isotope	Mass/ g	Isotope	Mass/ g
^{227}Ac	3.81x10^{-3}	^{129}I	8.60x10^{5}	^{79}Se	1.68x10^{4}
^{108m}Ag	14.90	^{93}Mo	963.70	^{151}Sm	1.20x10^{4}
^{241}Am	4.46x10^{6}	^{93m}Nb	56.76	^{121}Sn	2.68
^{242m}Am	7.15x10^{3}	^{94}Nb	1.08x10^{5}	^{126}Sn	3.28x10^{5}
^{243}Am	8.14x10^{5}	^{59}Ni	4.38x10^{6}	^{90}Sr	1.08x10^{5}
^{10}Be	34.41	^{63}Ni	2.73x10^{5}	^{99}Tc	4.58x10^{6}
^{14}C	9.11x10^{3}	^{237}Np	4.15x10^{6}	^{228}Th	6.76x10^{-3}
^{41}Ca	112.5	^{231}Pa	6.58	^{229}Th	0.12
^{36}Cl	2.79x10^{3}	^{210}Pb	3.27x10^{-3}	^{230}Th	616.1
^{243}Cm	121.40	^{107}Pd	1.35x10^{6}	^{232}Th	4.07x10^{3}
^{244}Cm	1.29x10^{3}	^{238}Pu	2.59x105^{5}	^{233}U	286.1
^{245}Cm	5.04x10^{3}	^{239}Pu	1.44x10^{7}	^{234}U	1.70x10^{6}
^{246}Cm	947.50	^{240}Pu	1.00x10^{7}	^{235}U	2.43x10^{7}
^{135}Cs	3.89x10^{6}	^{241}Pu	5.41x10^{3}	^{236}U	2.66x10^{7}
^{137}Cs	2.77x10^{5}	^{242}Pu	4.73x10^{6}	^{238}U	5.17x10^{9}
^{152}Eu	2.52x10^{-2}	^{226}Ra	0.39	^{93}Zr	4.73x10^{6}
^{3}H	0.18	^{228}Ra	1.63x10^{-6}		

Radionuclide Sorption Coefficients

The sorption coefficients of radionuclides in an environment containing bentonite are contained in Table B.2. They were taken from SKB's SR-Can documentation, as utilised in the generic post-closure safety assessment by RWM. Where a log-triangular function has been used, the three values in brackets represent the lower, median and upper bound. Those for the overlying geosphere (LSSR), based on Opalinus Clay data are displayed in Table B.3, and the overlying chalk in Table B.4.

Table B.2: Sorption coefficients for radionuclides in an environment containing bentonite.

Element	K^j_D/ $m^3.kg^{-1}$	Element	K^j_D/ $m^3.kg^{-1}$
Ac	LogTri(0.3, 8, 233)	Pu(III)	LogTri(10, 100, 984)
Ag	Uni(0, 15)	Pu(IV)	LogTri(4, 63, $1.11x10^3$)
Am	LogTri(10, 61, 378)	Pu(V)	LogTri(0.002, 0.02, 0.2)
C	0	Pu(VI)	LogTri(0.3, 3, 28)
Cl	0	Ra	LogTri($7.5x10^{-4}$, 0.0045, 0.027)
Cm	LogTri(10, 61, 378)	Se(-II)	0
Cs	LogTri(0.015, 0.093, 0.56)	Se(IV)	LogTri(0.003, 0.04, 0.4)
Eu	LogTri(0.8, 8, 93)	Sm	LogTri(0.8, 8, 93)
I	0	Sn	LogTri(2.3, 63, $1.76x10^3$)
Mb	0	Sr	LogTri($7.5x10^{-4}$, 0.0045 0.027)
Nb	LogTri(0.2, 3, 45)	Tc(IV)	LogTri(2.3, 63, $1.76x10^3$)

Ni	LogTri(0.03, 0.3, 3.3)	Tc(VII)	0
Np(IV)	LogTri(4, 63, 1.11x10^3)	Th	LogTri(6, 63, 700)
Np(V)	LogTri(0.004, 0.02, 0.2)	U(IV)	LogTri(3.6, 63, 1.11x10^3)
Pa	LogTri(0.2, 3, 45)	U(VI)	LogTri(0.5, 3, 18)
Pb	LogTri(12, 74, 457)	Zr	LogTri(0.1, 4, 103)
Pd	LogTri(0.3, 5, 75)		

Table B.3: Sorption coefficients for radionuclides in the clay environment.

Element	K^j_D/ $m^3.kg^{-1}$	Element	K^j_D/ $m^3.kg^{-1}$
Ac	LogTri(1, 10, 200)	Pa	LogTri(0.2, 5, 100)
Ag	0	Pb	LogTri(0.02, 2, 300)
Am	LogTri(1, 10, 200)	Pd	LogTri(0.2, 5, 100)
C	LogTri($5.4x10^{-6}$, 0.001, 0.054)	Pu(IV)	LogTri(1, 20, 300)
Cl	0	Ra	LogTri($5x10^{-5}$, $7x10^{-4}$, 0.026)
Cm	LogTri(1, 10, 200)	Se	0
Cs	LogTri(0.09, 0.5, 3)	Sm	LogTri(0.023, 5, 240)
Eu	LogTri(0.023, 5, 240)	Sn	LogTri(0.2, 100, 1000)
I	0	Sr	LogTri($6x10^{-5}$, 0.001 0.033)
Mb	LogTri(0.001, 0.01, 0.2)	Tc(IV)	LogTri(0.5, 20, 200)
Nb	LogTri($01x10^{-9}$, 4, 100)	Th	LogTri(10, 50, 200)
Ni	LogTri(0.03, 0.9, 20)	U(IV)	LogTri(0.5, 20, 200)
Np(IV)	LogTri(5, 50, 500)	Zr	LogTri(0.3, 10, 300)

Table B.4: Sorption coefficients for radionuclides in overlying chalk.

Element	K^j_D/ $m^3.kg^{-1}$	Element	K^j_D/ $m^3.kg^{-1}$
Ac	0	Pb	LogTri(0.002, 0.02, 0.2)
Ag	0	Pd	LogTri(0.0042, 0.042, 0.42)
Am	LogTri(0, 0.1, 10)	Pu(III)	LogTri(0.2, 2, 20)
C	LogTri($1.6x10^{-4}$, 0.0016, 0.016)	Pu(IV)	LogTri(0.0055, 0.055, 0.55)
Cl	0	Ra	LogTri($5x10^{-6}$, $5x10^{-5}$, $5x10^{-4}$)
Cm	LogTri(0.087, 0.87, 8.7)	Se(-II/VI*)	0
Cs	0	Sm	LogTri(0.036, 0.36, 3.6)
Eu	LogTri(0.036, 0.36, 3.6)	Sn	LogTri($3.8x10^{-5}$, $3.8x10^{-4}$, 0.0038)
I	0	Sr	LogTri($5x10^{-6}$, $5x10^{-5}$, 5x104)
Mb(VI)	0	Tc(IV/VII*)	0
Nb	0	Th	LogTri(0.0045, 0.045, 0.45)
Ni	LogTri($5x10^{-5}$, $5x10^{-4}$, 0.005)	U(IV)	LogTri(0.0095, 0.95, 0.95)
Np(IV)	LogTri(0.0055, 0.055, 0.55)	Zr	LogTri($8.5x10^{-5}$, $8.5x10^{-4}$, 0.0085)
Pa	LogTri($4.6x10^{-4}$, 0.0046, 0.046)		

Instant Release Fraction

The Instant Release Fraction (IRF) of a number of the radionuclides modelled were represented in the model according to the values presented in Table B.5.

Table B.5: Instant Release Fraction (IRF) % of radionuclides contained in spent AGR fuel.

Element	IRF %	Element	IRF %
^{14}C	NormTrun(20, 24.3, 0, 100)	^{107}Pd	NormTrun(0, 0.232, 0, 100)
^{36}Cl	10.3	^{108m}Ag	NormTrun(0, 0.232, 0, 100)
^{59}Ni	100	^{126}Sn	NormTrun(1.03, 0.175, 0, 100)
^{63}Ni	100	^{129}I	NormTrun(1.03, 0.175, 0, 100)
^{79}Se	NormTrun(1.03, 0.175, 0, 100)	^{135}Cs	NormTrun(1.03, 0.175, 0, 100)
^{90}Sr	NormTrun(0.125, 0.232, 0, 100)	^{137}Cs	NormTrun(1.03, 0.175, 0, 100)
^{99}Tc	NormTrun(0, 0.232, 0, 100)		

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Table C.1: Permissions to reproduce figures

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Appendix D - Stakeholder Survey Participants (Chapter 8)

The stakeholder survey conducted as part of Chapter 8 sought the opinions of a number of stakeholders in industry, regulators, local interest and authorities. Table D.1 (below) outlines the organisation and role of each stakeholder that took part in the survey:

Table D.1: Participants in Chapter 8 Stakeholder Survey.

Organisation	Role
ONR	Geological Disposal Lead
Environment Agency	Nuclear Regulations Group
RWM	Head of Health, Safety, Security, Environment and Quality
LLWR	Site Characterisation Manager
EDF	Director of Deconstruction & Transfer
NuLeaf	Executive Director
Cumbria County Council	County Councillor & Cabinet Member for Economic Development & Property

Appendix E- Author Publications

The author has produced two peer reviewed publications throughout the course of this PhD project:

- AI Marsh, LG Williams OBE, JA Lawrence, *The important role and performance of engineered barriers in a UK geological disposal facility for higher activity radioactive waste*, Progress in Nuclear Energy, July 2021, DOI: 10.1016/j.pnucene.2021.103736
- AI Marsh, LG Williams OBE, JA Lawrence, *A sensitivity study of the factors affecting the risks associated with the disposal of spent nuclear fuel in a geological disposal facility in a clay environment*, Progress in Nuclear Energy, October 2021, DOI: 10.1016/j.pnucene.2021.103910