Radioactive Waste Management

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Inventory for geological disposal

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Radioactive Waste Management Limited
Building 329
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Harwell Campus
Didcot
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UK

email: **rwmfeedback@nda.gov.uk**

Preface

This report is part of ongoing research by Radioactive Waste Management (RWM) and its contractors into implementing geological disposal for radioactive wastes in the UK.

Geological disposal is the UK Government's policy for the higher-activity radioactive wastes. The principle is isolation of the waste deep inside a suitable rock formation to prevent harmful quantities of radioactivity from reaching the surface. The waste will be placed in an engineered containment facility of tunnels and vaults constructed underground – a geological disposal facility (GDF). The facility will be designed so that multiple natural and man-made barriers work together to minimise the escape of radioactivity. Higher-activity radioactive wastes cover a range of categories including high level waste (HLW), spent nuclear fuel, intermediate level (ILW) and certain low level (LLW) radioactive wastes.

A GDF will be carefully designed and engineered. Typically, ILW and LLW would be encased in a cement grout and packaged in steel or concrete containers, for subsequent placement in the vaults. In time, the vaults would be backfilled with a cement-based material, completely surrounding the waste packages. Engineered barriers would be provided by the cement grout, the containers and the backfill. Natural barriers would be provided by geological formations surrounding the GDF and that lie between it and the accessible human environment. The concept for longer-lived HLW and spent nuclear fuel is slightly different: containers holding these materials would be placed directly into deposition tunnels, further apart from each other, again using engineered and natural barriers.

Executive Summary

The UK has been producing radioactive waste inventories for over 30 years and this is now a well-established iterative process. This report presents the 2019 inventory for geological disposal (IGD), which represents a 'light' update to the 2016 iteration. The IGD is based on Government policy, industry plans and publicly available information.

Data are presented on the quantity, activity, and material composition of the waste according to its classification, which in its simplest form is high and low heat-generating reflecting the relevant disposal concepts. The key points are that:

- the packaged volume of the 2019 IGD is estimated to be 773,000 m^3, while the total activity at 2200 is estimated to be 28,000,000 TBq.
- the low heat generating waste (i.e. low and intermediate level wastes, and depleted, natural and low enriched uranium) forms the majority of the 2019 IGD by packaged volume (nearly 90%) but contributes only a small fraction of the activity (less than 5%). Conversely, the high heat generating waste (fuels, plutonium and highly enriched uranium) makes only a small contribution to the packaged volume (roughly 10%) but dominates the activity (more than 95%).
- although waste and spent fuel from the assumed new build programme would dominate the activity for over 100,000 years after closure of the geological disposal facility, at extremely long times it is the legacy waste and spent fuel (specifically the depleted, natural and low enriched uranium) that would dominate the activity.

To support the assessment of non-radiological substances, the inventory for geological disposal now includes an estimate of the construction materials associated with a geological disposal facility.

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1 Introduction

1.1 The generic Disposal System Safety Case

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

A geological disposal facility (GDF) will be a highly engineered facility, located deep underground, where the waste will be isolated within a system of multiple man-made and natural barriers designed to prevent harmful quantities of radioactivity and non-radioactive contaminants from being released to the surface environment.

To identify potentially suitable sites for a GDF, the Government has developed an approach based on consent: working with interested communities that are willing to participate in the siting process [2]. No site has yet been identified for a GDF.

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

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

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

- high heat generating wastes (HHGW): that is, spent fuel from existing and future power stations and High Level Waste (HLW) from spent fuel reprocessing. High fissile activity wastes, that is, plutonium (Pu) and highly enriched uranium (HEU), are also included in this group. These have similar disposal requirements, even though they don't generate significant amounts of heat

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

- low heat generating wastes (LHGW): that is, Intermediate Level Waste (ILW) arising from the operation and decommissioning of reactors and other nuclear facilities, together with a small amount of Low Level Waste (LLW) that is unsuitable for near-surface disposal, and stocks of depleted, natural and low-enriched uranium (DNLEU)

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

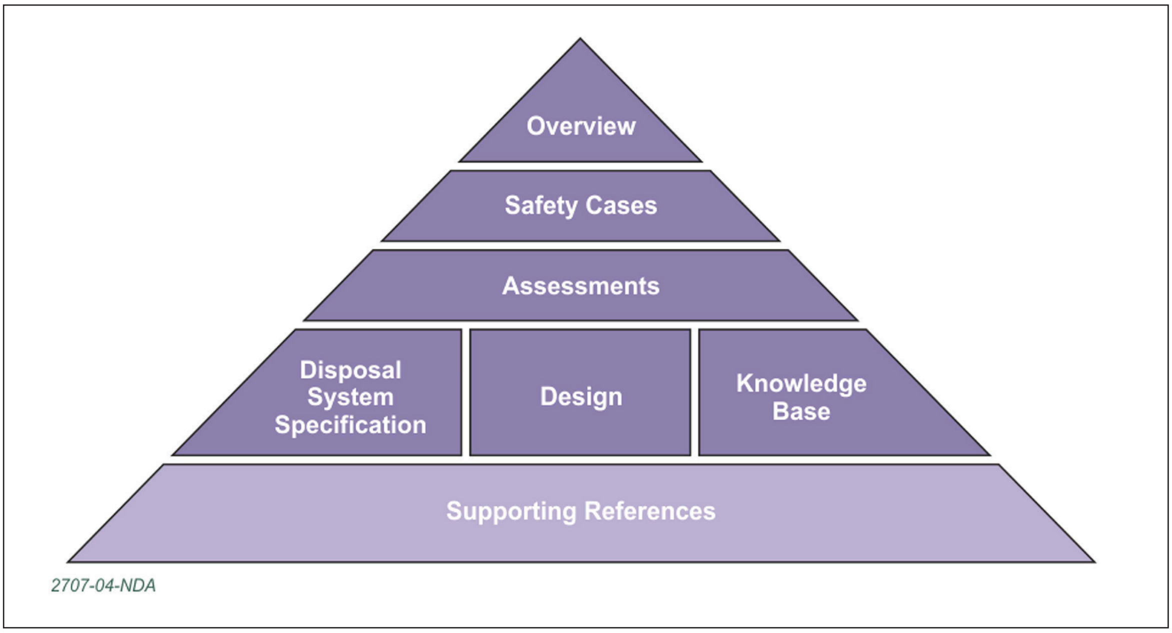
High level information on the inventory for disposal, the illustrative disposal concepts and other aspects of the disposal system is collated in a technical background document (the Technical Background) [3] that supports this generic Disposal System Safety Case.

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

The generic DSSC demonstrates that geological disposal can be implemented safely, and also forms a benchmark for RWM to provide waste producers with advice on packaging wastes for disposal.

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

Figure 1 - Structure of the generic DSSC



1.2 Introduction to the 2019 Inventory for Geological Disposal

This document is the '2019 inventory for geological disposal: main report'. It is one of five reports that deal with various aspects of the 2019 inventory for geological disposal (IGD) and previous IGDs. The other four reports are:

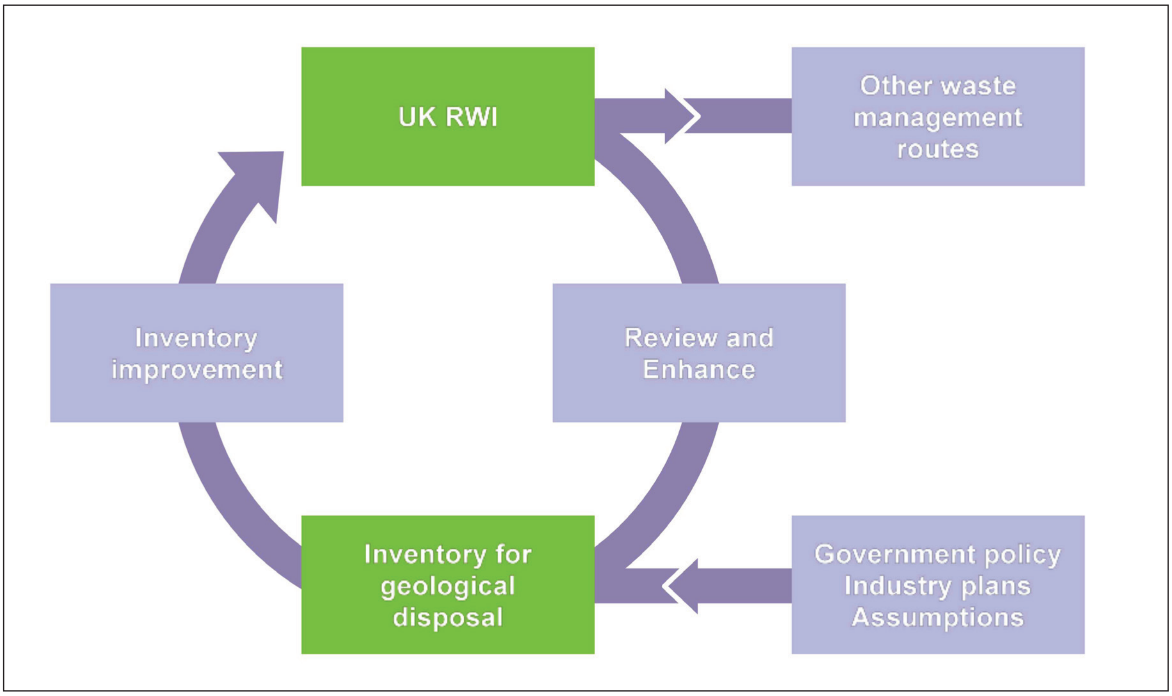
- the 'Method report' [4], which describes how IGDs are developed and updated
- the 'Differences report' [5], which sets out the differences between the 2019 IGD and the previous version (the 2016 IGD [6])
- the 'Implications report' [7], which describes the implications of the changes introduced by the 2019 IGD for the generic DSSC
- the 'Alternative scenarios report' [8], which provides information on how changes to the scenario for future arisings would affect the 2013 IGD [9], and which is updated in the differences report [5].

The IGD is based largely on the UK Radioactive Waste and Materials Inventory (RWI). The UK has been producing RWIs for over 30 years. The production process has been improved iteratively and is now well-established. Each UK RWI contains details of stocks and arisings of all radioactive waste from existing sources (often called legacy wastes).

Currently, the UK RWI is updated every three years, after which the IGD is updated, as shown in Figure 2. Waste that will be managed through other routes (eg waste that is destined for the Low Level Waste Repository (LLWR)) is removed from the UK RWI dataset and the remaining data are reviewed and, where appropriate, enhanced[2]. The dataset is further enhanced to take account of Government policy industry plans and other assumptions (these are discussed in sections 2.1 to 2.3) to produce the inventory for geological disposal. Finally, following the production of the UK RWI (and IGD), NDA and key users of the UK RWI (LLWR and RWM) meet with waste producers to discuss key inventory improvements. In addition, further characterisation of wastes is carried out to support decommissioning, leading to improvements in the inventory data. This iterative process drives continuous improvements in the UK RWI data and, consequently, the IGD.

[2] For the purposes of this work, 'review' is defined as the process of identifying omissions, differences and inconsistencies within the 2019 UK RWI itself, and with other sources of data. 'Enhancement' is defined as the process of filling gaps and providing fully justified numeric and other data where these are not reported in the 2019 UK RWI. For example, the UK RWI only provides the mass of spent fuels; the enhancement process adds the radionuclide activities and materials and packaging assumptions.

Figure 2 - The iterative development of the inventory for geological disposal



The most recent version of the UK RWI [10] is based on a stock date of 1st April 2019 and is referred to here as the 2019 UK RWI. The generic DSSC was published in 2016 and was based on the 2013 IGD [9], which in turn was based on the 2013 UK RWI [11].

The 2019 IGD is based on the 2019 UK RWI and is a 'light update' to the 2016 IGD. In a 'light update', the full review and enhancement process is not carried out: where waste streams are unchanged, the enhancements from the previous inventory are carried over. In addition, some calculations (for example, calculations of metal geometry to support the gas pathway analysis) are not carried out. The differences between a light update and a full update are explained in the Method report.

This report replaces the main report on the 2016 IGD [6] within the generic DSSC suite of documents.

1.3 Objective

The objective of the IGD is to provide information on the quantities and characteristics of the components of the inventory that is sufficiently detailed for use in RWM's design and safety and environmental assessment work.

This report presents detailed technical information and is targeted at an audience of scientists and engineers, in particular RWM staff and contractors who will use this information as a basis for generic geological disposal design and assessment work.

1.4 Scope

1.4.1 Definition of the inventory for geological disposal

The waste and material types that comprise the inventory for geological disposal are defined in paragraph 2.15 of an updated framework for the long-term management of higher-activity radioactive waste [2]:

2.15. The specific types of higher activity radioactive waste (and nuclear materials that could be declared as waste) which would comprise the inventory for disposal in a GDF are:

- *high level waste arising from the reprocessing of spent nuclear fuel at Sellafield;*
- *intermediate level waste arising from existing nuclear licensed sites, defence, medical, industrial, research and educational facilities;*
- *the small proportion of low level waste that is not suitable for disposal in the national Low Level Waste Repository;*
- *spent fuel from existing commercial reactors (yet to be declared waste) and research reactors that is not reprocessed;*
- *spent fuel (yet to be declared waste) and intermediate level waste from a new build programme up to a defined amount (see paragraphs 2.11, 6.54 and 6.55);*
- *plutonium stocks – plutonium not re-used in new fuel manufacture (yet to be declared waste);*
- *uranium stocks – including that arising from enrichment and fuel fabrication activities (yet to be declared waste); and*
- *irradiated fuel and nuclear materials (yet to be declared waste) from the UK defence programme.*

1.4.2 Waste groups

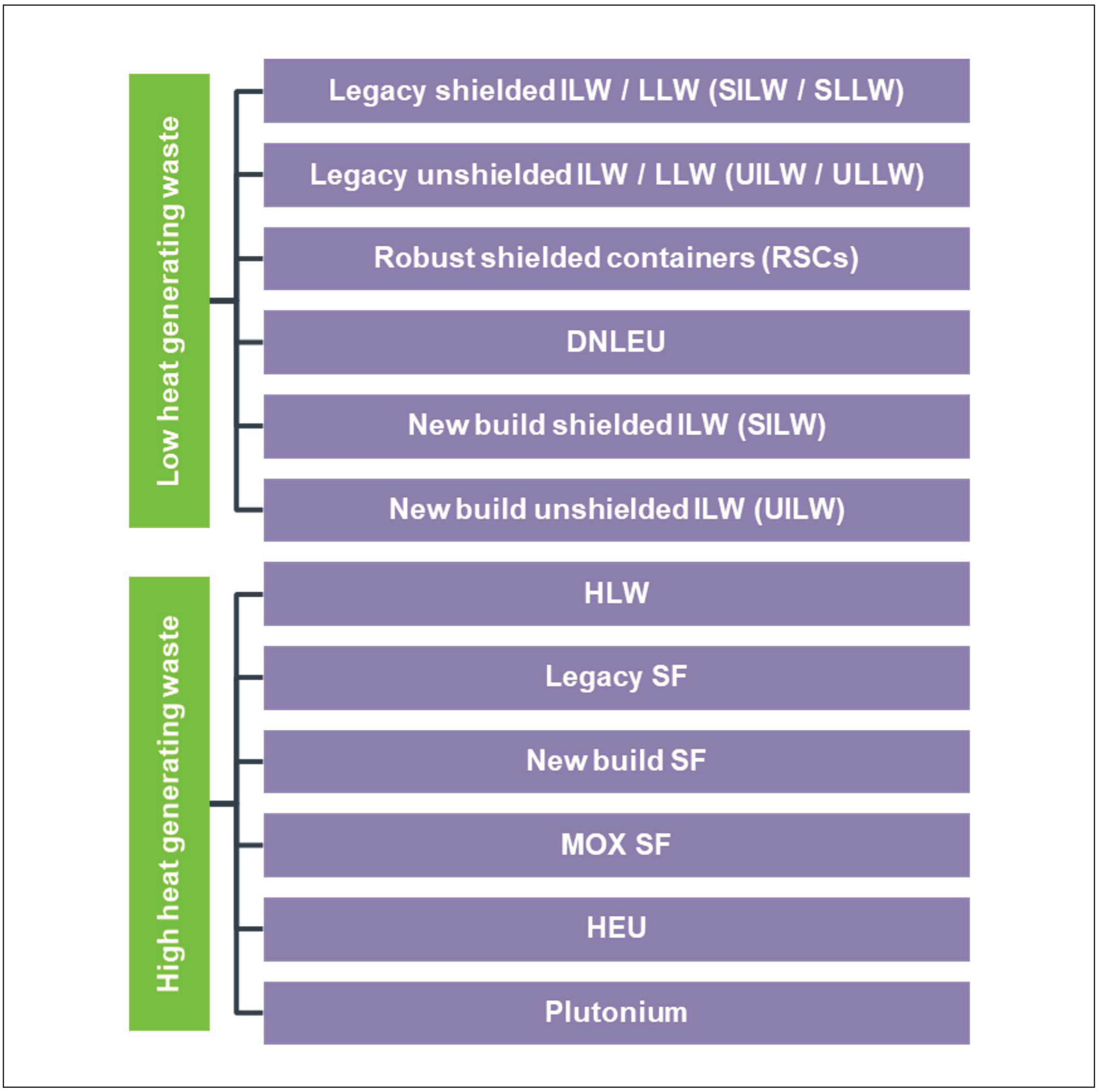
RWM's generic disposal facility designs [12] recognise the different packaging and disposal processes for different types of higher activity radioactive waste (HAW): LLW, ILW and DNLEU are assumed to be disposed of in a LHGW area; HLW, spent fuels (SFs), plutonium and HEU[3] are assumed to be disposed of in a HHGW area.

The inventory for geological disposal has been broken down into waste groups (shown in purple in Figure 3) that have been chosen to reflect the different sources of waste and how they will be disposed of in the GDF. The sources of waste considered are:

- legacy: wastes and materials that already exist or that will arise in the future as a result of the operation of existing nuclear facilities
- new build: wastes and spent fuels from the proposed new build programme
- mixed oxide (MOX): at this stage only spent fuel is included (see section 2.1.2)

[3] *HEU does not generate significant heat; it is included in the HHGW area as its disposal concept is very similar to that of the other HHGW.*

Figure 3 - The two high-level partitions of the inventory (green boxes) and the waste groups (purple boxes)



1.4.3 Data

Summary data for the 2019 inventory for geological disposal data are presented in Section 3, with a more detailed breakdown of the data by waste groups presented in the appendices. The data presented include:

- volumes: the stored, conditioned and packaged volume of the inventory
- activities: the IGD contains information on all 112 of the radionuclides identified as being relevant to geological disposal [13]. Data on key radionuclides are presented along with the total activity from all 112 'relevant radionuclides'
- the number of disposal units[4] associated with each type of package
- waste materials: the IGD contains waste material composition data on two levels: the bulk materials that make up the wastes, conditioning and capping materials and disposal containers; and elemental compositions. As this is a light update, the elemental compositions have not been revised from the 2013 IGD

[4] *A disposal unit is a waste package, or group of waste packages, which is handled as a single unit for the purposes of transport and disposal.*

Priority scores[5] for materials and radionuclides in the IGD were established through discussions with RWM safety case owners and experts in the areas of inventory, wasteform, packaging, transport, criticality and GDF design. The priority scores assigned to each material type and radionuclide were originally carried out in preparation of the 2004 IGD and the assignments have been reviewed for each 'full' update since. The 2019 IGD priority assignments are unchanged since the last full update (the 2013 IGD). The priority scores and justifications are reported in the inventory method report [4]. The priority materials are highlighted in the reported data. When reporting activities on individual radionuclides, only priority 1 radionuclides are included.

All data have been presented to three significant figures; this is considered to provide an appropriate quantification of the inventory data. In some cases, the data are not available or are not specified to three significant figures. In these cases, the data are presented to the level of precision to which they are known.

As a result of the rounding, some tables will show totals that may not represent the sum of the rounded data that are presented within them. Instead, the totals represent the sum of the data rounded to three significant figures. This approach ensures an appropriate and consistent level of precision in all the data.

1.4.4 Exclusions

The scope of this report excludes reporting the method for the production of the inventory and a consideration of different inventory scenarios. The method for producing the 2019 IGD is the same as that for the 2016 IGD, which is described in the 2016 IGD 'method report' [4]. Different inventory scenarios are explored in the 2019 IGD 'differences report' [5] using the scenarios considered in the 2013 IGD [8].

1.4.5 Report structure

The remainder of the report is structured as follows:

- Section 2 provides the basis of the quantified inventory for geological disposal
- Section 3 presents a summary of the inventory for geological disposal
- Section 4 contains a summary of the key messages

In addition, this report contains four appendices:

- Appendix A contains details of the 2019 IGD scenario
- Appendix B provides data broken down by waste group
- Appendix C presents summary tables
- Appendix D presents tables of the materials from GDF construction and operation

[5] *Priority scores are a measure of the importance of a data field to users of the IGD; scores range from 1 to 5, with priority score of 1 being the most important.*

2 Scenario for the inventory for geological disposal

Summary of the scenario for the inventory for geological disposal

The IGD is defined in the updated framework for the long-term management of higher activity radioactive waste. The IGD scenario is based on Government policy, industry plans and other publicly available information. This scenario represents RWM's best estimate of how the waste will arise. The key points are:

- quantities of legacy wastes and their times of arising are based on the data that waste producers have provided for the 2019 UK RWI
- HAW arising in Scotland is excluded from the IGD
- 95% of the civil plutonium stockpile is converted to MOX fuel and irradiated
- a new build programme of 16 GW(e) is included

The Implementing Geological Disposal - Working With Communities paper [2] defines the waste and material types that comprise the IGD (see Section 1.4.1). A scenario is used to describe how these waste and material types arise. The IGD scenario is RWM's best estimate of how the waste will arise; alternative scenarios are considered separately [8, 5].

The data for future waste arisings in the UK RWI are projections made by the organisations that operate the sites where radioactive waste is generated. The projections are based on informed assumptions as to the nature, scale and timing of future operations and activities. For the 2019 UK RWI, these projections represent planning assumptions at 1 April 2019. The UK RWI is the foundation of the scenario for the IGD but does not provide all the information that is required. As a result, several assumptions must be made to complete the IGD scenario; these are based on informed judgements.

Figure 4 is based on the 2019 IGD scenario and provides a high-level overview of the timings of the different activities; full details are provided in Table A1, while Table A2 provides details of the scenario broken down by waste group. The remainder of this section provides details and justifications for the assumptions in the 2019 IGD's scenario.

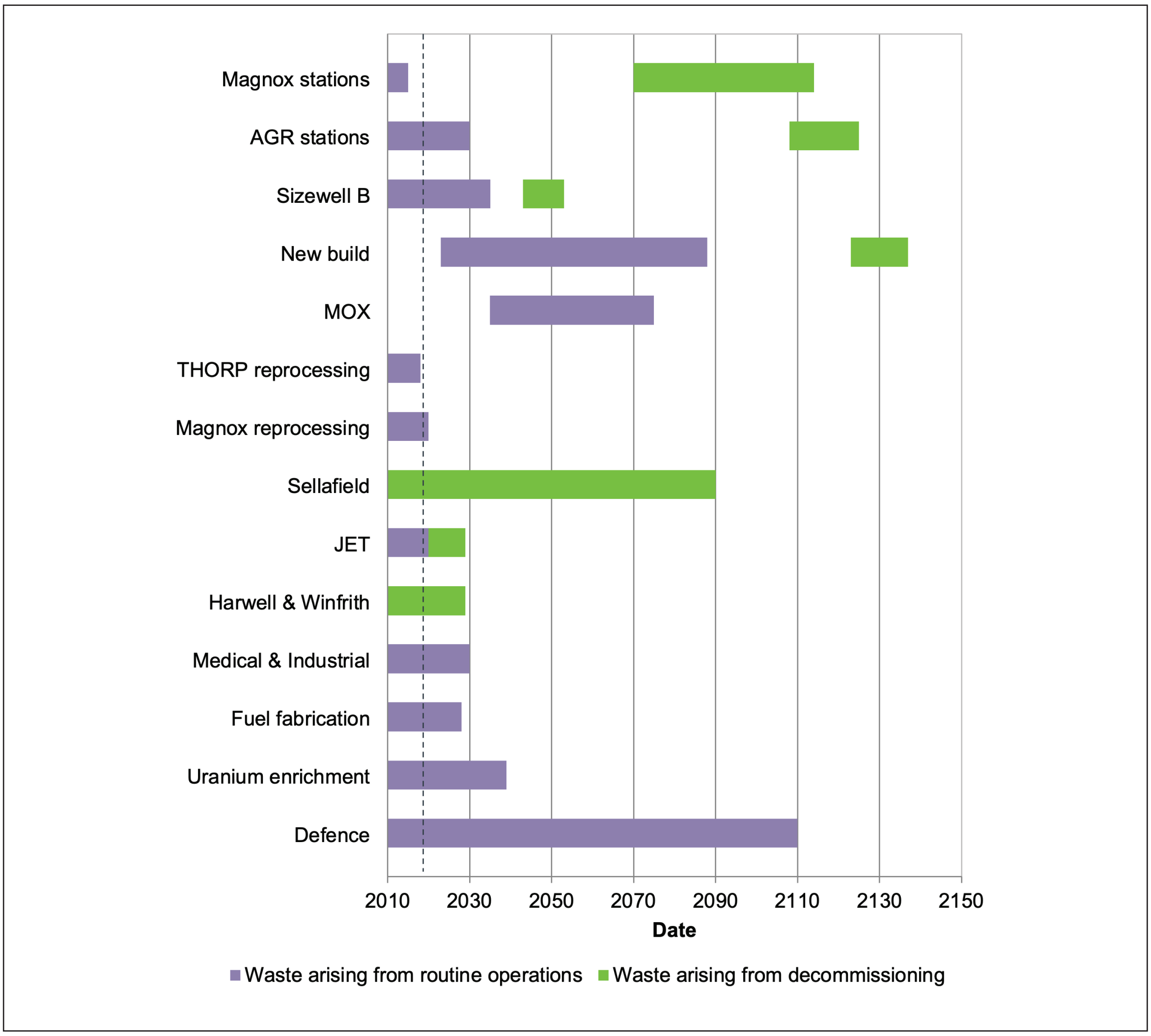
2.1 Government policy

2.1.1 Management of HAW in Scotland

Radioactive waste disposal is a devolved issue and policies differ across the UK. The policies of the UK Government [14, 2] and the Welsh Government [15] are that HAW in England and Wales should be managed in the long-term through geological disposal, coupled with safe and secure interim storage and ongoing research and development to support its optimised implementation.

The Scottish Government's policy is for the HAW arising in Scotland to be managed in near-surface facilities[6] [16]. Waste that is covered by the Scottish Government's policy[7] is therefore excluded from the IGD.

Figure 4 - The assumed dates of operation and decommissioning for activities that contribute to the 2019 IGD[8]. The dashed line indicates 2019



[6] *Facilities should be located as near to the site where the waste is produced as possible. Developers will need to demonstrate how the facilities will be monitored and how the waste packages, or waste, could be retrieved. All long-term waste management options will be subject to robust regulatory requirements. See paragraph 1.19 of reference [16].*

[7] *The policy does not cover radioactive wastes arising from the nuclear submarine bases on the Clyde, the Vulcan naval reactor test establishment, or the decommissioning and dismantling of redundant nuclear submarines. The policy does not apply to wastes that have been dealt with under the policies of previous governments.*

[8] *Decommissioning of the Magnox reprocessing plant and the thermal oxide reprocessing plant (THORP) are covered by Sellafield decommissioning. No decommissioning dates have been specified for 'Fuel fabrication', 'Medical and industrial', 'Enrichment' or 'Defence' as there is either no HAW decommissioning waste arising or the waste producer has not included an estimate of the decommissioning waste in the UK RWI. JET is the Joint European Torus.*

2.1.2 Management of plutonium

The UK Government's preferred policy for the long-term management of plutonium is that it should be re-used in the form of mixed oxide fuel [17]. The UK Government has not made any decision on the fate of the UK's plutonium stocks, and a discussion of the options can be found in the NDA's 'Progress on plutonium consolidation, storage and disposition' Paper [18]. The government would only be in a position to proceed when it was confident that its preferred option could be implemented safely and securely, was affordable, deliverable and offered value for money.

There is a range of options for using MOX fuel and the Government has yet to establish the most viable and cost-effective option. As a result, the assumptions regarding MOX have been decoupled from those for a new build programme. As such, the MOX spent fuel is considered as an addition to the spent fuels from new build. However, no nuclear power plant, MOX manufacturing plant or UO_2 fuel has been included.

In discussions with NDA, RWM has agreed that it is appropriate to assume that MOX is burned for a 40 year period starting in 2035. Arisings of MOX SF are assumed to be uniform over this 40 year period.

Uncertainties about the quantity of plutonium, and hence MOX SF, arise principally because:

- the assumed quantity of plutonium is based on predictions of the final reprocessing outturn, which have uncertainties associated with them; and
- government policy allows the UK to take title to overseas plutonium under commercial terms (see paragraph 1.8 of [17]) and it is uncertain whether this will occur

The fraction of the plutonium that will be suitable for manufacture into MOX fuel is also difficult to quantify. In discussions with NDA, it was agreed that 115 t was a reasonable estimate of the UK-owned plutonium at the end of reprocessing and that it was appropriate to assume that 95% of the 115 t of could be converted to MOX. The remaining 5% is assumed to be disposed of using the can-in-canister concept[9].

2.2 Industry plans

2.2.1 New build

The 2019 UK RWI does not contain information on wastes and SFs that might arise from new build reactors. Hence, it has been necessary to make assumptions regarding the size of the new build programme.

Because this is a light update to the 2016 IGD, and to retain consistency with the Implementing Geological Disposal – Working with Communities Paper[10], a 16 GW(e) new build programme is assumed. This is assumed to comprise six UK EPRs (each producing 1.6 GW(e)) and six AP1000s (each producing 1.14 GW(e)). However, it is acknowledged that:

- NNB GenCo (a subsidiary of EDF Energy) plans four UK EPRs, two at Hinkley Point, which are under construction, and two at Sizewell

[9] *In this concept, the waste is immobilised in a titanate-based puck. Twenty pucks are assumed to be loaded into a stainless steel can and 28 of these cans encapsulated in borosilicate glass within a large canister. This canister is placed in a disposal container. The can-in canister concept is non-optimal. However, until further work that justifies an alternative assumption has been completed, it remains the reference packaging assumption.*

[10] *See paragraph 6.55, which states that 'the spent fuel and intermediate level waste arising from new nuclear development up to this level constitutes the defined amount at present, though the pipeline could increase or decrease as new nuclear projects progress.' The size of the assumed new build programme will be reviewed ahead of the 2022 IGD, which is anticipated to be a full update.*

- Horizon Nuclear Power will cease its activities at Wylfa Newydd and Oldbury, where it had planned to construct UK advanced boiling water reactors (ABWRs)
- plans by NuGen for three AP1000 reactors at Moorside near Sellafield have been abandoned
- under a strategic investment agreement, China General Nuclear agreed to take a stake in the development of Hinkley Point C as well as jointly develop new nuclear power plants at Sizewell and Bradwell, with the new plant at Bradwell featuring the Hualong One design

These developments mean that there are uncertainties about the size, timing and composition of the new build programme. Some of these uncertainties are considered in an alternative inventory scenario [8] that contains the data required to assess the impact of additional reactors.

Inventory data for the UK EPR and the AP1000 has been taken from the disposability assessment reports [19, 20, 21, 22] published as part of the Generic Design Assessment (GDA) process [23]. Inventory data for the UK ABWR has also been published as part of the GDA process [24, 25]. As noted above, the UK ABWR is not included in the 2019 IGD; however, the inventory data associated with the UK ABWR are included in the alternative inventory scenarios report [8, 5]. A disposability assessment for the Hualong reactor noted above has not been published so no data for this reactor type is included in any of the 2019 IGD documents.

The assumed timetable for the reactors becoming operational is provided in Table 1[11]. Inventory data has been published for burn-ups of 50 GWd/tU and 65 GWd/tU and it has been assumed here that the fuel will have a burn-up of 65 GWd/tU. Both lead to a similar number of disposal containers since more of the lower burn-up assemblies can be disposed of in a single disposal container. The higher burn-up has been assumed as this maximises the inventory of higher actinides and, therefore, the neutron dose rate.

The 2019 IGD does not include any depleted uranium arising in the UK from uranium enrichment that is part of the manufacturing process for new build reactor fuel.

Table 1 - The number of reactors assumed to start operating each year

	2023	2024	2025	2026	2027	2028
UK EPR	2	2	2			
AP1000				2	2	2

2.3 Other assumptions

2.3.1 Legacy spent fuels

Whilst the UK RWI includes data on the quantity of SFs, at present it does not include any details of the waste materials that comprise the fuels, or their radionuclide inventories. It is necessary for RWM to make assumptions that allow the inventories to be calculated. Appendix A3 provides details of the assumptions made for the legacy SFs. The IGD includes both NDA-owned SFs and SFs owned by other organisations, eg SF from the Sizewell B reactor is owned by EDF.

[11] *It is acknowledged that Hinkley Point C will not be operational in 2023, and that the contracts incentivise operations starting in 2025. Similarly, the assumed start dates for other reactors may not be met. However, as this is a light update to the 2016 IGD, the assumptions regarding timing (which date back to the 2013 IGD) have been retained.*

The NDA inventory of spent fuels consists of large quantities of oxide fuels, along with smaller quantities of Magnox fuel and non-standard and diverse fuel types which are referred to as 'exotic fuels'.

AGR spent fuels are the largest part of the NDA's oxide fuel inventory. These fuels come from the seven EDF-owned AGR nuclear power stations in England and Scotland. NDA are contractually committed to receive and manage all of the AGR spent fuel arising from EDF's powers stations. For planning purposes, NDA assumes that all spent oxide fuels at Sellafield will be disposed of in a GDF.

NDA's current strategy is to reprocess as much of the spent Magnox fuel as is practicable. Some degraded metal fuels remain in or have been recovered from legacy ponds. As much of this material is heavily degraded, it is not suitable for reprocessing in existing facilities. NDA expect that, following a period of dry storage, the fuels recovered from the legacy ponds will be conditioned and disposed of as waste in a GDF.

NDA manage a small inventory of non-standard fuels, commonly referred to as 'exotic fuels'. These fuels include metallic, oxide and carbide materials. These exotic fuels arose from earlier nuclear industry activities such as the development of research, experimental and prototype fuels and reactors. Examples of exotic fuel types include fuels arising from the Dounreay Prototype Fast Reactor (PFR), the Windscale AGR reactor and the Steam Generating Heavy Water Reactor (SGHWR) at Winfrith.

The following fuel types are reported in the UK RWI [26, 27]: AGR, Sizewell B, light water reactor (LWR), PFR, SGHWR, WAGR and 'other fuels' at Sellafield. Incorporating these fuels in the IGD has required some assumptions to be made:

- Other fuels at Sellafield are said to include LWR fuels; these have been deducted from the total and the remainder is assumed to be metallic fuel (in generating a radionuclide inventory it has been assumed to be low burn-up Magnox fuel)
- The composition and packaging assumptions for miscellaneous LWR, WAGR and SGHWR fuel have been deduced based on analogy with PWR SF and known legacy fuel designs. These are preliminary assumptions that will be refined as more detail on the SF becomes available.

Further details of the assumptions that RWM have made relating to the fuels can be found in Appendix A3; this includes details of the parameters assumed in the calculation of the radionuclide inventories. The assumptions will be revisited as part of the 2022 IGD, which is anticipated to be a full update to the IGD.

2.3.2 Defence materials

The UK is an acknowledged Nuclear Weapons State under the Non-Proliferation Treaty and strategic materials are not destined for the GDF. However, for the purposes of developing the IGD, RWM has included MOD materials based on two assumptions:

- Where MOD and the NDA have similar materials these will be managed coherently in the public interest.
- Quantities have been estimated based on information in the public domain.

Irradiated submarine fuel

The Royal Navy's submarines have pressurised water reactors; submarine fuel differs from civil nuclear fuel. MOD fuel is classed as a zero-value asset. The MOD has not foreclosed the option to reprocess its fuel, however it is currently engaged in progressing a disposal option through RWM.

Key aspects of RWM's engagement with MOD will be understanding the conditions for disposal, which will inform the long-term planning strategy for irradiated fuel.

The mass of irradiated submarine fuel in the inventory for disposal will be significantly smaller than the contributions from legacy civil reactors. RWM considers that, at this stage, the inclusion of the irradiated submarine fuel in the inventory can be bounded by sensitivity studies on the quantities of these other fuels and the disposability issues associated with irradiated fuel can be taken into account in RWM's generic DSSC.

DNLEU

MOD uranium liabilities are approximately 15% (by mass) of NDA uranium liabilities; it is noted that the chemical forms are similar to NDA liabilities (eg oxides and hexafluoride) [28].

For the purposes of developing the IGD, RWM has assumed that the MOD has no unique DNLEU and its holdings can be managed in the same way as civil DNLEU[12].

HEU

The 1998 Strategic Defence Review [29] gives the UK stocks of HEU as 21.9 tU.

This strategic material is not destined for a GDF but for the purposes of developing the IGD, HEU is assumed to be managed in the same way as civil HEU: immobilised in a titanate-based ceramic that contains 11.9% HEU dioxide by mass, which would then be disposed of using the can-in-canister concept.

Plutonium

MOD plutonium liabilities within safeguards[13] are approximately 2% (by mass) of NDA plutonium liabilities, with similar chemical forms [28]. The 1998 Strategic Defence Review gives the UK stocks of defence Plutonium as 7.6t.

The strategic material is not destined for the GDF, but for the purpose of developing the IGD, RWM have assumed that the material is either suitable for re-use as MOX fuel, or can be disposed of if unsuitable and will be managed in a manner consistent with the civil plutonium.

2.3.3 Packaging assumptions

In order for a waste stream to be disposed of, it must have been accepted through RWM's Disposability Assessment process. The uncertainty associated with how waste will be packaged reduces as the waste progresses through the Disposability Assessment process. Characterisation of the waste, whether to support disposability assessment work or as part of the packaging of the waste reduces the uncertainty surrounding the material composition and radionuclide inventory of the waste. Figure 5 presents a schematic showing how the uncertainty surrounding the waste reduces with time.

[12] *It has been assumed that MOD DNLEU is packaged in the same way as Magnox Depleted Uranium.*

[13] *International Safeguards is the International Atomic Energy Agency's system to verify that nuclear material is not being diverted for use in nuclear weapons or other explosive devices from nominally peaceful applications.*

The conditioned and packaged waste volumes presented in this report are projections based on current and forecast methods of preparing wastes for long-term management. Uncertainty in waste packaging assumptions is not considered here; it is considered in RWM's alternative inventory scenarios report.

In preparing the inventory for geological disposal, RWM reviews the waste containers assigned to the ILW and LLW by waste producers; this may result in the waste containers being reassigned for some waste streams.

Review of waste container assignments

As this is a light update to the 2016 IGD, waste streams that are unchanged from the 2016 UK RWI have had their enhancements from the 2016 IGD carried over. For new waste streams (or those that have changed) the packaging assumptions are reviewed where:

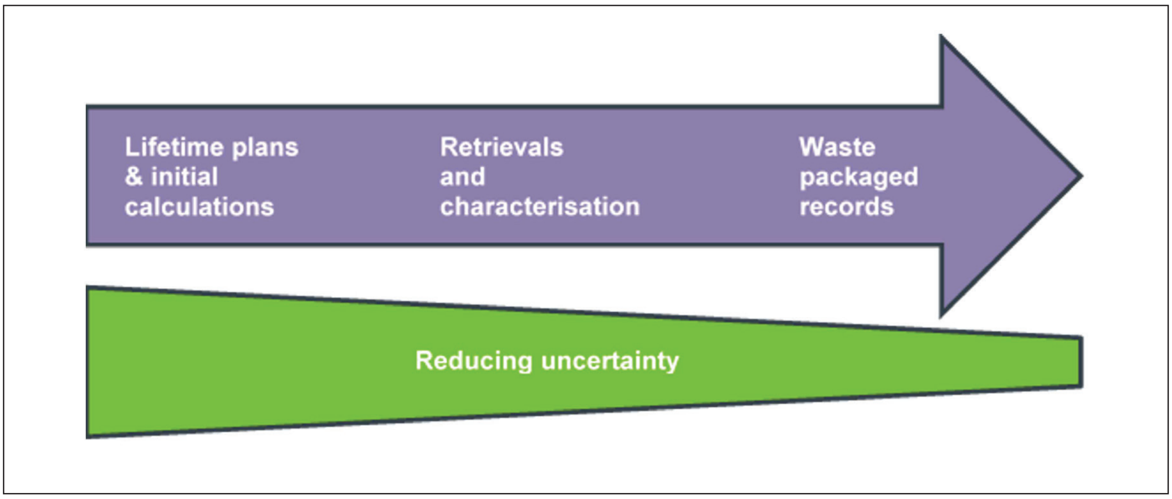
- the waste container has not been specified
- RWM has thought it necessary to review the waste container type[14]
- a non-standard waste container is specified[15]
- a waste stream has been allocated more than one container type

A further verification of the chosen container is carried out based on the dose rate and heat output of the waste packages: where these have exceeded the transport limits by greater than 25%, a new waste container type is assigned.

The most significant result of the review of waste container assignments relates to 3 m^3 decommissioning concrete containers reported by Sellafield and TRU-Shield containers. These waste containers have not completed RWM's change management process and there is not an associated detailed waste package specification. The waste package assignment has therefore been changed for the IGD:

- Magnox wastes that were assigned to TRU-Shield containers in the 2019 UK RWI have been reassigned to 500 l drums
- Sellafield wastes that were assigned to 3 m^3 decommissioning concrete containers in the 2019 UK RWI have been reassigned to 3 m^3 enhanced Sellafield boxes.

Figure 5 - Reducing uncertainty in the packaging and characterisation of the waste



[14] *For example, where the dose rate could be high or the packaging efficiency is low.*

[15] *For ILW and LLW, the 2019 IGD only uses waste containers that have completed RWM's change management process and have a detailed waste package specification. The UK RWI does not specify waste containers for HLW, SFs or nuclear materials.*

LHGW waste containers

RWM's illustrative geological disposal concepts for LHGW are based on three broad categories of waste container: unshielded, shielded and robust shielded packages. For ILW and LLW, RWM has a suite of waste package specifications that define the requirements for the transport and geological disposal of waste packages manufactured using standardised designs of waste container.

The UK RWI does not provide information on the packaging of DNLEU and there are no formal designs for waste containers that would be used for its packaging. However, based on the preferred options identified by RWM's uranium integrated project team [30], the IGD makes the following packaging assumptions for the DNLEU that is less than 1% enriched and for Defence DNLEU:

- the current / planned wasteform for storage would be used for disposal (i.e. unencapsulated UO_3 and U_3O_8 powders)
- the powders will remain in their current / planned storage containers:
    - depleted uranium tails (U_3O_8 powder) in mild steel DV-70s
    - older Magnox depleted uranium (MDU) (UO_3 powder) in mild steel 200 l drums that have been overpacked in larger (approximately 500 l) stainless steel drums
    - more recent MDU (UO_3 powder) in 210 l stainless steel drums
- the current / planned storage containers would be disposed of in a stainless steel transport and disposal container (TDC), which is a 20-foot IP-2 rated International Organisation for Standardisation (ISO) container:
    - 2.3 m high and containing four DV-70s for depleted uranium tails
    - 2.4 m high and containing twenty-eight 200 l drums overpacked in approximately 500 l drums for older MDU and Defence DU
    - 2.1 m high and containing fifty-four 210 l drums for more recent MDU
- the TDCs will be infilled with a 3:1 mixture of BFS / PFA:OPC grout prior to disposal

The remaining DNLEU (ie miscellaneous DNLEU, THORP product uranium (TPU) and uranium tetrafluoride) is assumed to be converted into a triuranium octoxide (U_3O_8) powder, which would be mixed with a pulverised fuel ash:Ordinary Portland cement (PFA:OPC) encapsulant and repackaged into 500 l drums for disposal.

HHGW waste containers

The UK RWI does not provide any information on the packaging of HHGW. As a result, the packages must be assigned by RWM. RWM has defined illustrative geological disposal concept examples for HLW and spent fuels in a range of potentially suitable UK geological environments[16] [3]. Detailed design work has been carried out for HLW, AGR SF and PWR SF [31]. Two container variants were considered:

- Variant 1: a disposal container designed for a higher strength host rock and based on SKB's copper / cast iron KBS-3 disposal canister concept [32]
- Variant 2: a disposal container designed for a lower strength sedimentary host rock and based on NAGRA's mild steel disposal concept [33]

For the purposes of quantifying the inventory for geological disposal, it is assumed that the Variant 1 container is used. The differences between the two variants are mainly in the materials used and masses; the volumes are very similar.

[16] *These are not necessarily the concepts that RWM will implement in the relevant geological setting; at this stage no disposal concept has been ruled out*

The inventory for geological disposal includes other spent fuels, and the packaging assumptions for these are assumed to be similar to those for AGR SF and PWR SF (ie, a copper container with a cast iron insert).

Plutonium residues and HEU are also assumed to be packaged in a copper disposal container with a cast iron insert. In these cases, it is assumed that: the material would be immobilised in a titanate-based puck; twenty pucks would be loaded into a stainless steel can; 28 of these cans would be encapsulated in borosilicate glass within a large canister; this canister is placed in the disposal container.

2.3.4 Others

The UK RWI includes ILW streams that waste producers expect to manage as LLW by using radioactive decay storage and / or decontamination processes[17]. Some combustible wastes are expected to be incinerated and some metal wastes are expected to be recycled. However, only those ILW streams where there is an established decontamination or incineration process are excluded from the inventory for geological disposal[18]. All other ILW waste streams that are expected to be managed as LLW will continue to be included in the inventory for disposal until incineration, recycling or disposal routes other than geological disposal are authorised.

The inventory for geological disposal includes LLW in the UK RWI that is identified as unsuitable for consignment to the LLWR and which is not being treated by incineration or being recycled. LLW streams unsuitable for consignment to the LLWR that are being treated by incineration or are recycled are not included in the inventory for geological disposal. Any residues from treating these wastes are expected to have very small volumes and contain insignificant quantities of radionuclides in comparison with total quantities in the inventory for geological disposal.

A proportion of the waste from THORP and the Magnox reprocessing plant at Sellafield results from the reprocessing of overseas spent fuels. All reprocessing contracts with overseas customers that have been signed since 1976 include a provision to return packaged wastes to the country of origin. Waste substitution arrangements are currently being implemented whereby an additional amount of HLW from reprocessing is returned instead of the ILW and LLW associated with the reprocessing of the customers' spent fuels. The HLW is smaller in volume but equivalent to the ILW and LLW in radiological terms. The IGD excludes all HLW that will be exported and includes the ILW that remains in the UK (all LLW from overseas fuel reprocessing is suitable for consignment to the LLWR and so is not included).

It has been assumed when producing the IGD that a facility (or facilities) for the disposal of LLW continues to be available, and that the waste acceptance criteria will be similar to those currently being applied at the LLWR.

Superplasticisers

The 2019 IGD assumes that superplasticisers comprise 0.5 wt% of all cementitious waste materials. This assumption is thought to be bounding and, for legacy facilities, it is unlikely that it will be possible to obtain any data; however, information may be available for the waste containers and capping / conditioning grouts in existing waste packages. In addition, RWM has completed work on superplasticisers [34], which shows that the use of polycarboxylate ether (PCE) superplasticisers is acceptable in a number of situations. As a result, the use of superplasticisers in future packages should be easier to quantify, and it may be possible to improve the estimate of superplasticisers (both the quantity and type) in the inventory.

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[17] *The 2019 UK RWI includes 31 such waste streams.*

[18] *For the 2019 IGD these are 3L24 and 7A32.*

3 The inventory for geological disposal

Summary of the inventory for geological disposal

The stored volume of the 2019 IGD is estimated to be approximately 342,000 m^3, less than 8% of the stored volume of wastes reported in the 2019 UK RWI.

The total packaged volume of the 2019 IGD is estimated to be approximately 773,000 m^3, of which just over 10% is attributable to an assumed new build programme. The total packaged volume is dominated by the LHGW, which contributes more than 80%.

The activity of the 2019 IGD at 2200 is estimated to be 28,000,000 TBq and this is dominated by the spent fuels. New build spent fuel dominates the activity for over 100,000 years after GDF closure but at extremely long times DNLEU activity dominates.

The total mass of waste materials for the 2019 IGD is estimated to be 539,000 t. The breakdown by mass of stored wasteform is approximately: 19% metals; 2% organics; 78% inorganics; and 0.5% unspecified.

An estimate of the construction materials associated with each of the three generic host geologies has been provided.

This section presents summary information for the whole inventory; **Appendix B** presents a more detailed breakdown of the inventory data by the waste groups shown in **Figure 3.** The data presented in this report are estimates based on the 2019 IGD scenario described in **Section 2**.

3.1 Volumes

As shown in **Figure 2**, the production of the IGD starts from the UK RWI. Those wastes that are not destined for a geological disposal facility are removed and additional wastes, eg from an assumed new build programme, are added. **Figure 6** shows[19] the routing of the wastes in the UK RWI, and also those wastes that are not reported in the UK RWI: MOD materials (see **Section 2.3.2**) and wastes from an assumed 16 GW(e) new build programme (see **Section 2.2.1**). It can be seen that:

- the stored volume of waste from an assumed 16 GW(e) new build programme is small in comparison to the total

[19] *The thicknesses of the lines are proportional to the stored volume of the waste. Only the masses of uranium, plutonium and spent fuels are reported in the UK RWI; the stored volumes are based on assumptions made by RWM. As this figure deals with stored volume, there is no MOX fuel, instead the volume of plutonium is included. The contribution of wastes from a new build programme is shown separately, as is the contribution of the MOD uranium and plutonium. No estimate of irradiated submarine fuel has been included. VLLW is very low level waste.*

- the stored volume of MOD materials is small in comparison to the total
- only a small fraction of the UK RWI wastes is destined for a GDF: the stored volume of the wastes in the 2019 IGD (approximately 342,000 m^3) is less than 8% of the stored volume of the wastes reported in the UK RWI (approximately 4,560,000 m^3)

Table 2 presents the total stored, conditioned and packaged volume of waste in the 2019 IGD broken down into six broad waste categories. The volume of the waste is dominated by the ILW and uranium, and the proportion of the volume attributable to the spent fuels, Pu and HLW increases significantly once packaging is taken into account.

Table 3 presents a breakdown of the packaged volume by waste group. The packaged volume of the 2019 IGD is dominated by low heat generating wastes: between them, the Legacy UILW / ULLW, DNLEU and Legacy SILW / SLLW contribute over 80% of the packaged volume of the waste. The ILW and spent fuel from the assumed new build programme contribute just over 10% of the total packaged volume.

Figure 7 shows the increase in the packaged volume of the 2019 IGD with time broken down by waste group. The rate at which the packaged volume increases is greatest from the present until 2039, when enrichment activities are assumed to stop. All the waste has arisen by 2137.

Figure 6 - The routing of the UK RWI wastes (by stored volume). Wastes from other sources that are added to the IGD by RWM are also shown

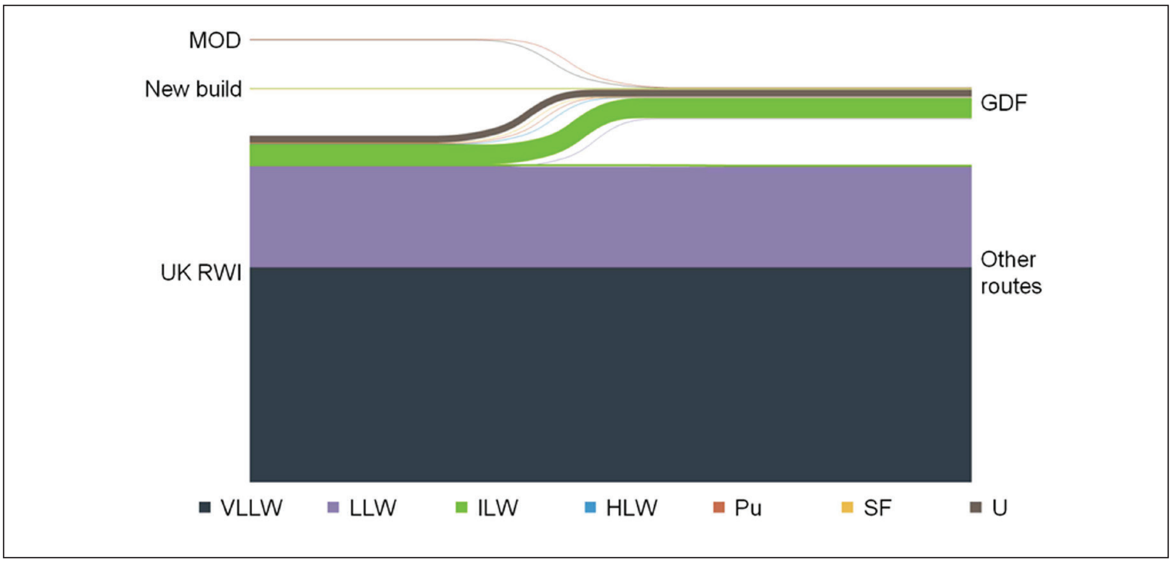


Table 2 - Total volume of waste[20]

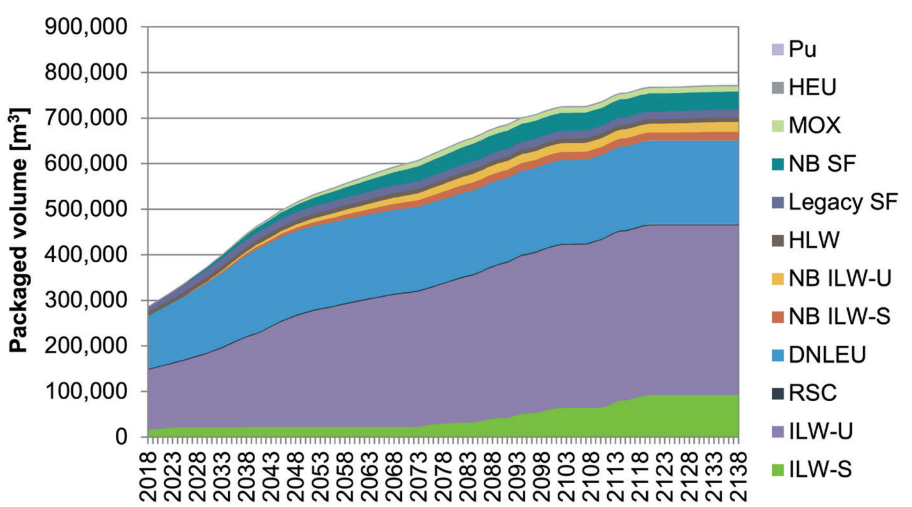
Waste category	Stored volume [m^3]	Conditioned volume [m^3]	Packaged volume [m^3]
HLW	1,500	1,500	9,880
ILW	229,000	370,000	503,000
LLW	3,830	4,810	5,110
Pu	0.567	174	620
Spent fuels	10,300	10,300	68,400
U	97,200	135,000	186,000
Total	342,000	522,000	773,000

[20] *Volumes are rounded so subtotals do not sum to totals*

Table 3 - Packaged volume associated with each of the waste groups

Waste group	Volume [m³]	Fraction of total [%]
Legacy SILW / SLLW	92,600	12%
Legacy UILW / ULLW	372,000	48%
RSCs	2,610	0.3%
DNLEU	184,000	24%
NB SILW	18,900	2%
NB UILW	22,100	3%
HLW	9,880	1%
Legacy SF	17,000	2%
NB SF	39,400	5%
MOX SF	11,900	2%
HEU	2,470	0.3%
Pu	620	0.1%
Total	773,000	n/a

Figure 7 - The arisings profile of the 2019 IGD broken down by waste group



3.1.1 Waste origin by operation

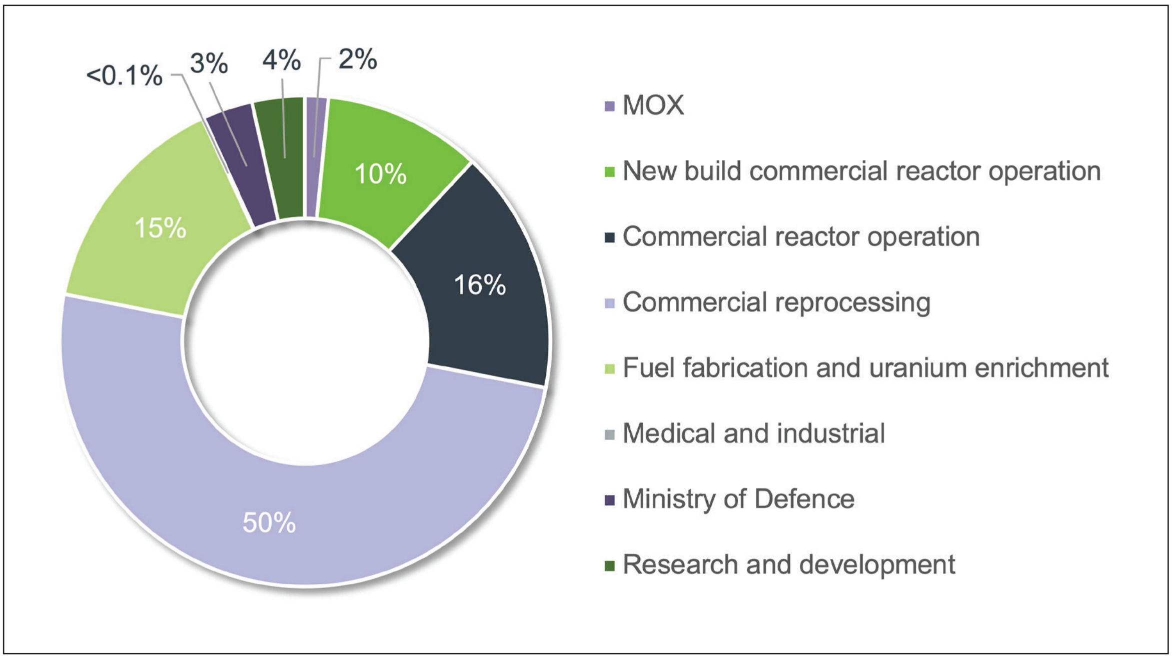
HAW has been produced in the UK through electricity generation, defence activities and other industrial, medical and research activities. HAW continues to be produced from these activities and further waste is projected from a programme of new nuclear power stations.

[Figure 8] shows a breakdown of the packaged volume of wastes in the IGD by the type of operation from which they originate. The following types of operation are included:

- use of MOX spent fuel
- new build commercial reactor operation
- commercial reactor operation (includes wastes from Magnox reactors, AGRs and Sizewell B)
- Sellafield (includes wastes from reprocessing and other activities at Sellafield[21])
- fuel fabrication and enrichment (includes wastes from Springfields and Capenhurst)
- medical and industrial (includes wastes from GE Healthcare, the LLWR and minor waste producers)
- MOD
- research and development (includes wastes from Harwell, Windscale, Winfrith, Culham and Berkeley)

As would be expected, the packaged volume of the waste is dominated by nuclear fuel cycle activities and reactor operations. Medical and industrial contribute less than 0.1%.

Figure 8 - A breakdown of the packaged volume by origin



3.2 Disposal units

GDF throughput is measured in terms of disposal units. Most waste packages are handled singularly as disposal units; however, four 500 l drums are handled together in a stillage, which is a single disposal unit. The estimated numbers of disposal units in each waste group is presented in **Table 4**. The legacy UILW / ULLW waste group dominates the number of disposal units; this is consistent with the fact that this waste group dominates the packaged volume. However, the DNLEU waste group, which contributes 24% of the packaged volume, only contributes 5% of the disposal units. This is because a significant proportion of this waste group is packaged in TDCs, which are large in comparison to other waste packages.

Appendix B contains full details of each waste group, including details of the types of packages.

[21] *Only wastes from the historically separate licensed sites of Windscale and Calder Hall are excluded; these wastes are included under the 'nuclear energy research and development' and 'commercial reactor operation' industries, respectively.*

Table 4 - The number of disposal units associated with each waste group

Waste group	Disposal units [-]	Fraction of total [%]
Legacy SILW / SLLW	5,050	3%
Legacy UILW / ULLW	126,000	71%
RSCs	949	0.5%
DNLEU	8,380	5%
NB SILW	10,100	6%
NB UILW	8,230	5%
HLW	2,550	1%
Legacy SF	4,160	2%
NB SF	8,940	5%
MOX SF	2,710	2%
HEU	780	0.4%
Pu	196	0.1%
Total	178,000	n/a

3.3 Radioactivity

The activity associated with the 2019 IGD at 2200 is estimated to be 28,000,000 TBq. The breakdown of the activity into the different waste groups is shown in Table 5. The activity is dominated by the spent fuels: 67% of the activity is attributable to the new build spent fuels, while 13% is attributable to MOX SF, and 10% to the legacy SFs. Less than 5% of the total activity is associated with LHGW.

The activity of priority 1[22] radionuclides at 2040 and 2200 are presented in Table 6. Whilst it might be expected that the activities would decrease between 2040 and 2200, the fact that waste is still arising in between these dates (see Figure 7) means that this is not always the case. For the radionuclides that are long-lived with respect to the time difference, for example U-238, the activity increases between 2040 and 2200; for radionuclides that are short-lived with respect to the time difference, such as Co-60, the activity reduces between 2040 and 2200 despite there being additional arisings.

[22] *Highest priority score for those radionuclides having greatest effect on wasteform, packaging, transport, criticality and GDF design*

Table 5 - The activity associated with each of the waste groups at 2200

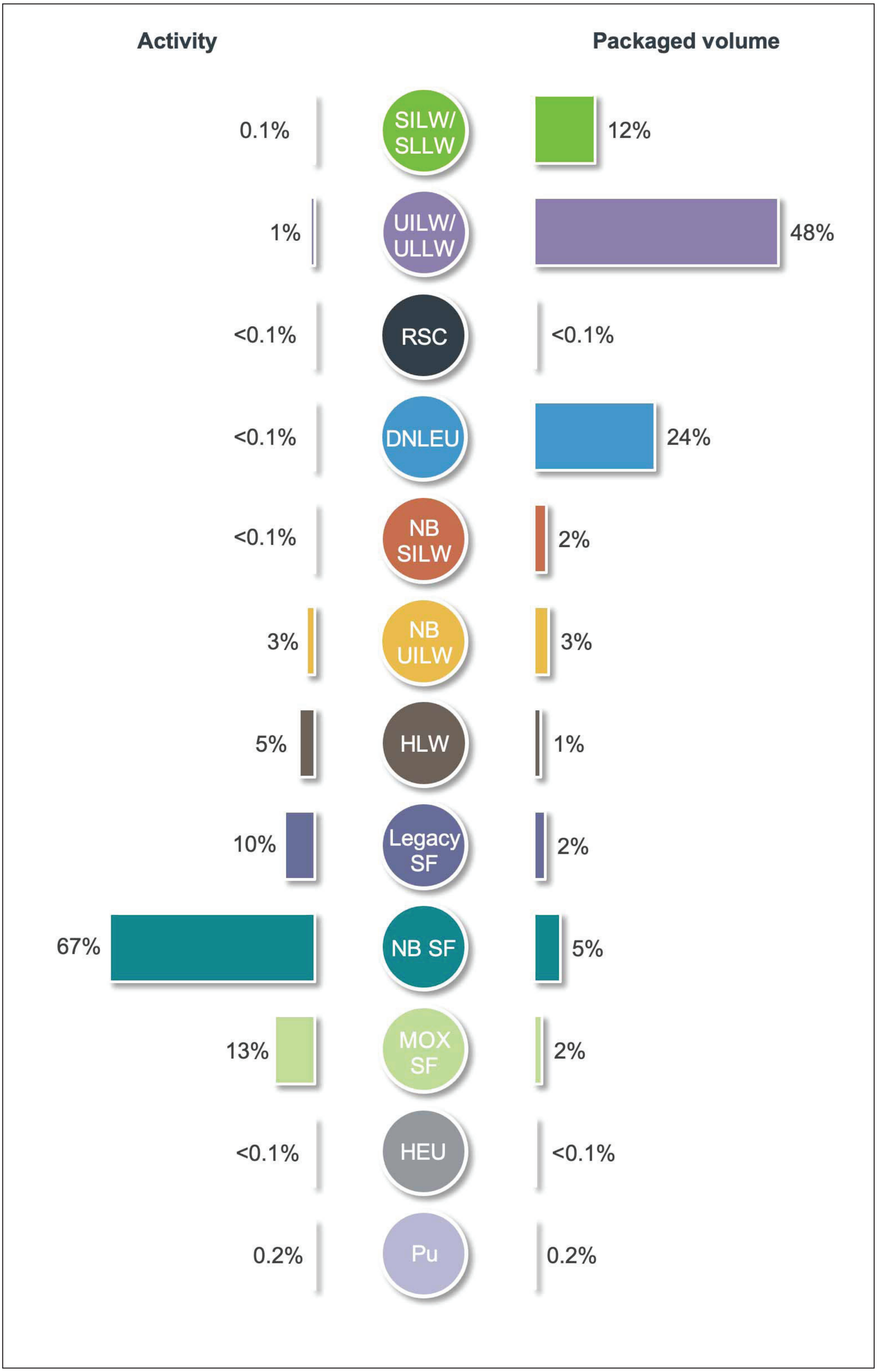
Waste group	Activity [TBq]	Fraction of total [%]
Legacy SILW / SLLW	19,400	<0.1%
Legacy UILW / ULLW	398,000	1%
RSCs	3,180	<0.1%
DNLEU	9,800	<0.1%
NB SILW	154	<0.1%
NB UILW	793,000	3%
HLW	1,460,000	5%
Legacy SF	2,780,000	10%
NB SF	19,000,000	67%
MOX SF	3,700,000	13%
HEU	53.7	<0.1%
Pu	43,700	0.2%
Total	28,200,000	n/a

Table 6 - Activity associated with the priority 1 radionuclides at 2040 and 2200

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	2,370	17,800	Cs-135	534	986
Cl-36	28.0	110	Cs-137	53,400,000	5,210,000
Co-60	745,000	2.12	U-233	1.55	2.49
Se-79	52.6	103	U-235	66.4	72.2
Kr-85	1,880,000	1,250	U-238	2,660	2,850
Tc-99	10,000	20,700	Np-237	315	881
I-129	17.1	43.6			

Figure 9 shows a comparison of the volume and the activity (at 2200) associated with each waste group; those waste groups that have a large volume tend to have a small activity, and vice-versa. New build spent fuel dominates the activity for over 100,000 years after GDF closure but DNLEU dominates the activity at extremely long times.

Figure 9 - Comparison of the fraction of the activity (at 2200) and volume associated with each waste group



Although new build spent fuel dominates the activity at early times, legacy wastes and SF dominate the activity at later times. This is because the shorter-lived fission products will have decayed (reducing the activity of the spent fuels), whilst the longer-lived radionuclides (eg naturally occurring uranium isotope U-238) from DNLEU persist. Indeed, the activity associated with DNLEU initially increases with time as the short-lived daughters of the uranium isotopes grow in. These short-lived daughters are present in natural uranium ore but are removed when the material is refined. **Figure 10** shows the evolution of the activities of the different waste groups with time. The increase in the activity of DNLEU waste group is clear. Whilst new build wastes dominate at early times, this is not always the case. This is illustrated more clearly in **Figure 11**.

Figure 10 - The evolution of the total activity of key waste groups. Minor contributors have been grouped into 'Others'

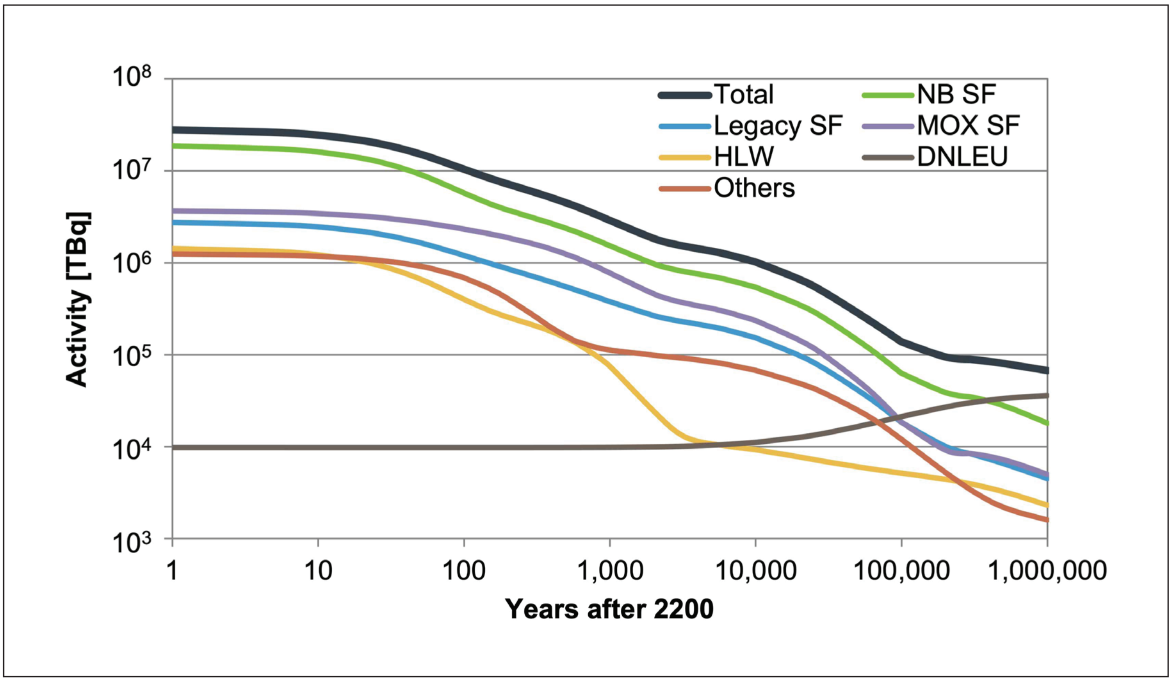
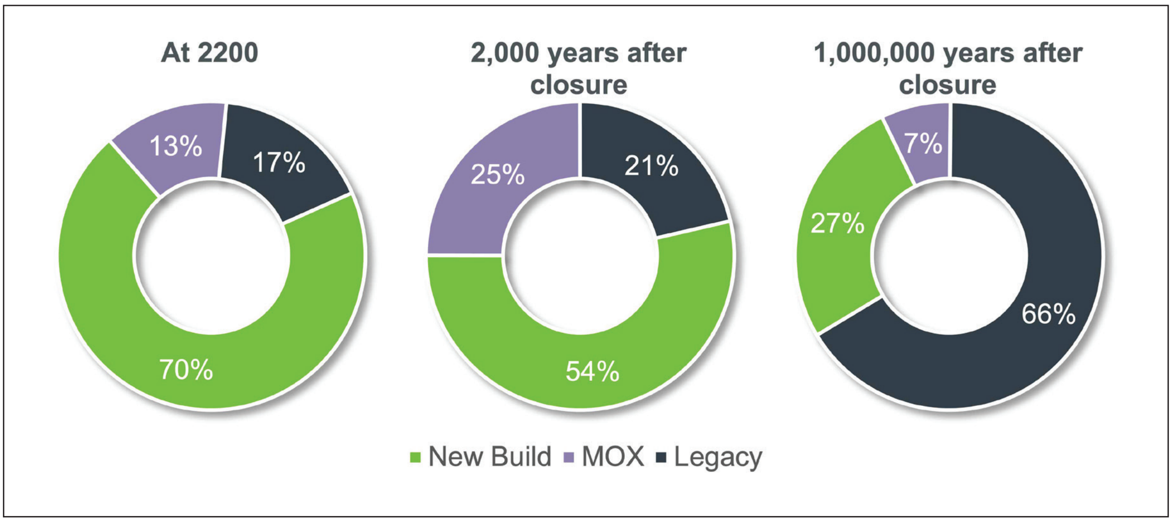


Figure 11 - The fraction of the total activity that is attributable to wastes and materials from new build, MOX and legacy facilities at GDF closure (2200), 2000 years and 1,000,000 years after closure



It should be noted that these fractions are sensitive to the assumptions regarding the new build programme; however, the general conclusions are expected to apply regardless of the number and design of new facilities.

3.4 Materials data

The IGD considers two types of material that will be present in the GDF: materials associated with waste packages; and materials from GDF construction and operation. This is the first time that the latter have been included in the IGD.

3.4.1 Broad categories of materials associated with waste packages

Table 7 shows the waste materials that make up the IGD split into three broad categories: metals, organics and inorganics. The data presented only take account of the stored form of the waste. Where the waste has been conditioned, this will include the conditioning matrix. However, in general, the data exclude materials associated with conditioning and capping of the waste, as well as any materials associated with the waste packages.

It can be seen in Table 7 that the inventory is dominated by inorganics, which account for approximately 78% of the inventory by mass; metals account for approximately 19% by mass, and organics approximately 2%. The remainder (approximately 0.5% by mass) is not specified. Appendix B discusses the breakdown of the waste materials in each waste group, while Appendix C includes data on the masses of the waste materials that make up the capping and conditioning matrix, as well as the waste materials associated with the waste packages.

It is assumed that superplasticisers are present in cements used in the construction of legacy facilities, some of which will be disposed of to a GDF. The chemical composition of superplasticisers means that they could complex with actinides and potentially increase their solubility. Consistent with the 2016 IGD, the 2019 IGD adopts a conservative assumption that all cementitious materials (including wastes, encapsulating and capping materials and waste containers) contain 0.5 wt% superplasticiser.

Table 7 - The waste material masses and the percentage of the total mass

	Waste group	Mass [t]	Percentage of total [%]
Metals	Aluminium (and alloys)	1,030	0.2%
	Copper (and alloys)	305	0.1%
	Iron	3,190	0.6%
	Lead	754	0.1%
	Magnox / magnesium	6,670	1.2%
	Nickel (and alloys)	282	0.1%
	Other ferrous metals[23]	46,100	8.6%
	Stainless Steel	36,300	6.7%
	Uranium	1,820	0.3%
	Zircaloy / Zirconium	6,330	1.2%
	Other metals	297	0.1%
	Total metals	103,000	19.1%
Organics	Cellulose	1,070	0.2%
	Halogenated plastics	3,100	0.6%
	Hydrocarbons	45.3	<0.1%
	Non-halogenated plastics	1,480	0.3%
	Organic ion ex. Resins	3,460	0.6%
	Rubbers	1,100	0.2%
	Other Organics	127	<0.1%
	Total organics	10,400	1.9%
Other materials	Asbestos	65.9	<0.1%
	Cementitious materials[24]	57,400	10.6%
	Graphite	70,700	13.1%
	Glass, ceramics, sand	4,010	0.7%
	Heavy metal oxide	253,000	46.9%
	Ion ex. Materials	5,160	1.0%
	Sludges & flocs	20,900	3.9%
	Soil, brick, stone & rubble	1,070	0.2%
	Other inorganics	10,400	1.9%
	Total other materials	422,000	78.4%
	Total unspecified	2,840	0.5%

[23] *Principally mild steel.*

[24] *All cementitious materials are assumed to contain 0.5 wt% superplasticiser.*

3.4.2 Materials from GDF construction and operating equipment

Some equipment and materials used for construction and operation of the GDF will remain in situ underground after closure. For example, crane rails used in the emplacement of waste packages in vaults, engineering barriers such as the backfill material and any plugs and seals. In addition, some materials that are required to ensure the integrity of the GDF during operations (eg concrete, rock bolts, some electronics and monitoring systems) will remain after GDF closure. This material will contribute to the total inventory of non-radiological substances and processes such as gas generation; it is therefore important that it is recorded so that it can be included in RWM's safety case work. The exact nature and quantity of this equipment will not be fully determined until the GDF site has been selected and the GDF design finalised. However, estimates have been made based on:

- The illustrative generic GDF designs in each of the three host rocks considered in RWM's generic DSSC: higher strength rock, lower strength sedimentary rock and evaporite rock
- Existing equipment commonly used to construct and operate underground facilities
- Other equipment associated with nuclear facilities

The equipment was further broken down into constituent key material types.

It is noted that the GDF designs, the equipment used, and the material composition of this equipment, are all subject to change.

The construction and operation materials that will remain underground after closure are estimated:

- per vault for LHGW and per disposal tunnel for HHGW; this allows the estimates to be scaled to the appropriate number of vaults / tunnels
- for the whole GDF for the 'shafts and drift' and common service areas'

Appendix D presents estimates for each of the key material types for each of the three host rocks.

3.4.3 Hazardous materials and non-hazardous pollutants

The Environmental Permitting (England and Wales) Regulations 2016 [35] give effect to certain provisions of Directive 2000/60/EC (Water Framework Directive) [36] and Directive 2006/118/EC (Groundwater Daughter Directive) [37] in England and Wales. It is noted that the legislation governing Scotland [38] and Northern Ireland [39] is different to that governing England and Wales.

The Environmental Permitting (England and Wales) Regulations 2016 prevent anyone carrying out an activity (such as geological disposal) that might result in the input of pollutants into groundwater unless they have been granted a permit to do so by the relevant environment agency. In granting a permit for such an activity, the relevant agency must ensure that inputs of hazardous substances to groundwater will be prevented and inputs of non-hazardous pollutants will be limited so as to avoid pollution. This will require RWM to inform the relevant agency of the quantities of hazardous substances and non-hazardous pollutants that will be present in a geological disposal system and demonstrate the adequacy of the controls it will have in place to prevent and limit (respectively) inputs of these substances to groundwater.

Following a screening exercise by RWM to identify reporting requirements for hazardous substances and non-hazardous pollutants, several new materials have been added to the UK RWI (and therefore the IGD). These are in addition to the hazardous substances and non-hazardous pollutants that were already present in the UK RWI and IGD.

4 Key messages

Summary of key messages

The IGD is based on Government policy, industry plans and publicly available information. Most of the data for legacy wastes and materials are taken from the UK Radioactive Waste Inventory. The development of the inventory is an iterative process and RWM's work on hazardous substances and non-hazardous pollutants has informed new reporting requirements that have been incorporated in the IGD.

Most of the activity in the inventory is located in a very small volume of waste. The activity associated with the inventory decays quickly and, whilst spent fuel and wastes from an assumed new build programme dominate for over 100,000 years after GDF closure, it is the legacy wastes and materials that dominate at extremely long times.

An estimate of the construction materials associated with each of the three generic host geologies has been provided for the first time.

The UK has been producing radioactive waste inventories for over 30 years; this is a well-established process. This report presents the 2019 IGD, which is a light update to the 2016 IGD and, as such, carries over many of the assumptions from the 2016 IGD.

The inventory for geological disposal is based on Government policy, industry plans and other publicly available information; the key assumptions are presented in Section 2:

- quantities of legacy wastes and their times of arising are taken from the UK RWI
- wastes covered by the Scottish Government's policy for the management of higher activity radioactive wastes are assumed to be disposed of via other routes
- 95% of the civil plutonium stockpile is assumed to have been converted to MOX fuel
- assumptions have been made regarding the physical / chemical form and radionuclide inventory of the legacy spent fuels, uranium, plutonium and MOX SF
- an assumed new build programme of 16 GW(e) has been included
- the quantities of MOD materials are based on the MOD Nuclear Liabilities Management Strategy [28] and the strategic defence review [29]
- HHGW are assumed to be disposed of in high-integrity disposal containers
- LHGW are assumed to be disposed of in an approved container type

Data have been presented on the quantity, activity, and material composition of the waste. The key points are that:

- the volume is dominated by the LHGW waste groups, which make a small contribution to the total activity at 2200 (the assumed date of GDF closure)
- at 2200 the activity is dominated by the spent fuel waste groups, which make only a small contribution to the volume
- although waste and spent fuel from the assumed new build programme dominate for over 100,000 years after GDF closure, it is the legacy wastes and materials that dominate at extremely long times

Estimates of GDF construction materials in the three generic host geologies are supplied. These estimates are based on the illustrative generic GDF designs. Data are presented per vault / tunnel, so that estimates can be scaled to the appropriate size of a GDF.

The development of the inventory is an iterative process. In the 2019 iteration, RWM has adapted the IGD to the evolving needs of its users by including additional information to support assessments of hazardous substances and non-hazardous pollutants. RWM will continue to evolve the IGD to ensure that it meets the needs of its users.

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Glossary

Term	Definition
ABWR	Advanced Boiling Water Reactor
AGR	Advanced Gas-cooled Reactor
AP1000	Pressurised water reactor sold by Westinghouse Electric Company
BFS	Blast furnace slag
Conditioned volume	The conditioned waste volume is the volume of the wasteform (waste plus immobilising medium) within the container
Cooling time	Average time after the irradiation of fuel elements in a reactor stops
Disposal unit	A waste package, or group of waste packages, which is handled as a single unit for the purposes of transport and disposal.
DNLEU	Depleted, natural and low enriched uranium
DSSC	Disposal system safety case
DU	Depleted uranium
DU tails	Depleted Uranium left over from enrichment operations
EPR	EPR is now used by AREVA as a reactor name, it was previously used to mean European Pressurized Reactor and Evolutionary Power Reactor
ESC	Environmental safety case
GDA	Generic design assessment
GDF	Geological Disposal Facility
gESA	generic Environmental Safety Assessment
gOSC	generic Operational Safety Case
gTSC	Generic Transport Safety Case
GWd/tU	Gigawatt days per tonne of uranium (1 tonne = 1,000 kg)
GW(e)	Gigawatts electrical
HAW	Higher activity radioactive waste
HEU	Highly-enriched uranium
HHGW	High heat generating waste
HLW	High level waste

Term	Definition
IGD	Inventory for geological disposal
ILW	Intermediate level waste
ISO	International organisation for standardization
JET	Joint European Torus
LAW	Low active waste
Legacy waste	Radioactive waste which already exists or whose arising is committed in future by the operation of an existing facility
LEU	Low enriched uranium
LHGW	Low heat generating waste. Some wastes have negligible heat output; these are included in this category
LLW	Low level waste
LLWR	Low Level Waste Repository
LWR	Light Water Reactor
MBGWS	Mixed Beta Gamma Waste Store
MDU	Magnox depleted uranium
MOD	Ministry of Defence
MOX	Mixed oxide fuel
NB	New build
OPC	Ordinary Portland cement
OSC	Operational safety case
Packaged volume	The packaged waste volume is the displacement volume of a container used to package a wasteform
Payload	Usable internal volume of a waste package
PFA	Pulverised fuel ash
PFR	Prototype Fast Reactor
Priority 1 radionuclide	Highest priority score for those radionuclides having greatest effect on, wasteform, packaging, transport, criticality and GDF design
Pu	Plutonium
PWR	Pressurised Water Reactor
RS	Robust shielded
RSC	Robust shielded container
SF(s)	Spent fuel(s): nuclear fuel removed from a reactor following irradiation that is no longer usable in its present form because of depletion of fissile material, poison build-up or radiation damage
SGHWR	Steam-generating heavy water reactor
SILW	Shielded ILW
SILW waste package	Waste package not requiring additional shielding

Term	Definition
SLLW	Shielded LLW
SS	Stainless steel
Superplasticiser	Commonly used to improve the flow characteristics of cements and concrete and also allow the water to cement ratio to be reduced (this produces stronger concretes). Superplasticisers could enhance the solubility of actinides
SWTC	Standard Waste Transport Container
t	Tonne (1 tonne or 1 metric ton = 1,000 kg)
TDC	Transport and disposal container
tHM	Tons of heavy metal (1 tonne = 1,000 kg)
THORP	Thermal oxide reprocessing plant
TPU	THORP product uranium
tU	Tons of uranium (1 tonne = 1,000 kg)
UILW	Unshielded ILW
UILW waste package	Waste package requiring additional shielding
UK RWI	UK radioactive waste inventory (also referred to as UK RWMI - UK radioactive waste and materials inventory)
ULLW	Unshielded LLW
VLLW	Very low level waste
WAGR	Windscale advanced gas-cooled reactor
WVP	Waste Vitrification Plant

Appendix A - 2019 IGD Scenario

A1 Timings and durations of activities

Table A1 - The timings and durations of activities in the 2019 IGD scenario

Sector	Assumptions[25]
Civil nuclear power stations	Sizewell B shuts down in 2035 AGRs: Shuts down in 2023: Hinkley Point B, Hunterston B Shuts down in 2024: Heysham 1, Hartlepool Shuts down in 2028: Dungeness B Shuts down in 2030: Heysham 2 Deferral of Magnox and AGR final stage decommissioning for up to about 85 years after shutdown; all decommissioning complete by 2125 Prompt decommissioning of Sizewell B (completed by 2053) New build programme of 16 GW(e) comprising 6 UK EPRs and 6 AP1000s. 60 years operation each; deferral of decommissioning until 40 years after reactor shutdown
Pu	95% of civil (and all MOD) Pu re-used as MOX fuel 5% of civil Pu treated as waste
U enrichment	Continues until 2039
SF reprocessing	Magnox fuel reprocessing continues until 2020 (55,000 tU in total) All reprocessing facilities fully decommissioned by 2090 5,500 tU AGR SF is not reprocessed Sizewell B SF, new build SFs and MOX SF are not reprocessed
Research	The Joint European Torus (JET) operates until end of 2020
Harwell & Winfrith	All redundant facilities are fully decommissioned by 2027
Defence	A continuing nuclear defence capability (waste estimated to 2080) A continuing nuclear powered submarine programme (waste estimated to 2110)
Medical & industrial sources	The medical uses of radioactivity continue (arisings estimated to 2030)
Fuel fabrication	Continues until 2028 (although no operational or decommissioning HAW is produced in the manufacturing process)

[25] *Excludes wastes managed under the Scottish Government's Policy for HAW.*

A2 Assumptions regarding quantities

Table A2 - The estimated contents of each waste group

Waste Group	2019 IGD[26]
SILW / SLLW UILW / ULLW RSCs	All 2019 UK RWI ILW, excluding those wastes with an established management strategy of incineration, recycling or near surface disposal All 2019 UK RWI LLW unsuitable for near-surface disposal
DNLEU	184,000 tU from civil fuel enrichment and civil spent fuel reprocessing 8,000 tU from defence programmes
NB SILW NB UILW	ILW from a 16 GW(e) new build programme
HLW[27]	All 2019 UK RWI HLW from reprocessing 55,000 tU Magnox SF and 5,000 tU Advanced gas-cooled reactor (AGR) SF
Legacy SF	SF to be managed by EDF 1,050 tU Sizewell B Pressurised Water Reactor (PWR) SF SF to be managed by NDA Oxide: 5,500 tU AGR SF Magnox (assumed): 723 tU metallic SF Exotic: 68 tU SGHWR SF 20.8 tU WAGR SF 66 tU miscellaneous LWR SF 10 tHM PFR SF[28] Fuel not quantified Irradiated submarine fuel
NB SF	8,260 tU UK EPR SF 6,030 tU AP1000 SF
MOX SF	1,460 tHM MOX SF (includes fuel made from defence Pu) 8%wt Pu
HEU	1.0 tU from civil programmes 21.9 tU from defence programmes
Pu	5.75 tPu separated Pu residues from reprocessing of civil SFs (representing 5% of the 115 tPu UK owned Pu unsuitable for re-use as MOX fuel)

[26] *Excludes wastes that are managed under the Scottish Government's Policy for HAW.*

[27] *Note that a small portion of HLW created from reprocessing UK SFs will be returned to overseas customers under waste substitution arrangements that are described further in* Section 2.3.4.

[28] *In previous iterations of the IGD PFR SF has been referred to as 'exotic SF' as it was the only exotic SF quantified.*

A3 2019 IGD scenario: spent fuel enhancements

The UK RWI only presents information on the masses of the spent fuels. RWM has made assumptions regarding the level of irradiation that these fuels have received (see Table A3). In the case of AGR fuel, it is assumed that the arisings can be divided evenly between the two enrichments of the robust fuel [A1].

In addition to the assumptions regarding the irradiation conditions, RWM has had to make assumptions regarding the material composition of the fuels; these are presented in Table A4.

Table A3 - Key parameters in the calculation of the fuel inventories[29]

Spent fuel type	Enrichment [%]	Burn-up [GWd/tHM]	Cooling time [years]
AGR (pre-2013)	2.9	28	12
AGR (post-2013)	3.2 / 3.78	33	Arises as 1 yr cooled
Sizewell B (pre-2013)	4.2	45	14
Sizewell B (post-2013)	4.4	55	Arises as 1 yr cooled
Metallic fuels	0.71	4.1	42
SGHWR	3.9	40	29
WAGR	2.85	18.2	38
Miscellaneous LWR	3.9	40	19
PFR	(Pu) 29.5	189	25
MOX SF	(Pu) 8	50	Arises as 1 yr cooled
UK EPR SF	5	65	Arises as 1 yr cooled
AP1000 SF	4.5	65	Arises as 1 yr cooled

Table A4 - Bulk materials per disposal container

	Component	Material	Mass [t]
PFR	Fuel	UO_2 / PuO_2 (U/Pu)	0.624 (0.550)
	Cladding	Nimonic	0.166
	SS canisters	Type 304 SS	0.488
AGR	Fuel	UO_2 (U)	2.34 (2.06)
	Cladding	Type 20/25 Nb SS	0.282[30]
	Sintox discs	Al_2O_3	0.016
	Slotted cans	Type 316 SS	0.197

[29] *Note that the inventories for the new build spent fuels are included for completeness only. The radionuclide inventories are taken from the GDA disposability assessment reports and have not been enhanced by RWM.*

[30] *Consistent with the 2013 Derived Inventory, the radionuclide activity used for AGR SF has assumed 0.27 t of cladding.*

Table A4 - Bulk materials per disposal container (Continued)

	Component	Material	Mass [t]
Sizewell B PWR	Fuel	UO_2 (U)	2.08 (1.834)
	Cladding[31]	Zircaloy 4	0.4688
	Plenum springs	Type 304 SS	$9.60\ 10^{-3}$
	Grids	Inconel 718	$2.68\ 10^{-2}$
	Grid sleeves	Type 304 SS	$4.80\ 10^{-3}$
	Top & bottom nozzles[32]	Type 304 SS	$5.04\ 10^{-2}$
Magnox[33]	Fuel	Uranium metal	0.886
	Cladding[34]	Magnox Al80	0.159
	WVP canisters	Type 309 SS	0.381
WAGR	Fuel	UO2 (U)	2.34 (2.06)
	Cladding[35]	Type 20/25 Nb SS	0.282
	Slotted cans	Type 316 SS	0.197
SGHWR	Fuel	UO2 (U)	2.34 (2.06)
	Cladding	Type 20/25 Nb SS	0.282
	Slotted cans	Type 316 SS	0.197
Misc. LWR	Fuel	UO_2 (U)	2.08 (1.834)
	Cladding	Zircaloy 2	0.4688
	Plenum springs	Type 304 SS	$9.60\ 10^{-3}$
	Grids	Inconel 718	$2.68\ 10^{-2}$
	Grid sleeves	Type 304 SS	$4.80\ 10^{-3}$
	Top & bottom nozzles	Type 304 SS	$5.04\ 10^{-2}$
UK EPR	Fuel	UO2 (U)	1.79 (1.58)
	Cladding, grids, etc	Zircaloy M5	0.486
	Springs	Inconel 718	$1.31\ 10^{-2}$
	Nozzles	AISI 304L SS	$4.38\ 10^{-2}$
	Insulating pellets	Al_2O_3	$1.79\ 10^{-3}$
AP1000	Fuel	UO_2 (U)	1.84 (1.62)
	Cladding, grids, etc	Zirlo	0.469
	Springs	Inconel 718	$1.55\ 10^{-2}$
	Nozzles	Type 304 SS	$4.37\ 10^{-2}$
	Insulating pellets	Al_2O_3	$1.70\ 10^{-3}$

[31] *Note that for the arisings this is assumed to be M5 and not Zircaloy 4.*

[32] *This mass is reduced to 10% of the stated value in the activation calculations in order to model the reduced flux that is experienced at the ends of the fuel assembly.*

[33] *Averages for five different Magnox fuel elements are used for the fuel and cladding masses:*
Calder Hall / Chapelcross: total element mass 13.2 kg; uranium mass 11.4 kg
Dungeness A: total element mass 12.9 kg; uranium mass 11.0 kg
Sizewell A: total element mass 14.0 kg; uranium mass 11.9 kg
Oldbury: total element mass 12.9 kg; uranium mass 10.6 kg

[34] *Mass includes stainless steel sheathed bottom cone (mass unknown).*

[35] *WAGR SF consists of stainless steel clad or beryllium clad fuel pins, for the 2019 IGD they have all been assumed to be stainless steel clad.*

Appendix A References

A1. HSE, NP/SC 7439 – *The safety case for the use of 'Robust Fuel'*,2011/146846, 2011.

Appendix B - Inventory data by waste group

In this appendix a separate section is used to present the inventory data for each of the waste groups. In each case, the same data are presented:

- information on volumes
- information on the number of disposal units
- information on the activity
- information on the materials

The sections contain only a brief discussion of the materials data; Appendix C presents detailed data.

As the 2019 IGD is a light update to the inventory, the following have not been calculated:

- the gas generation parameters (metal geometry / thicknesses)
- the elemental composition of the waste

As such, no data are presented on these. The most up to-date information on these parameters are published in the 2013 IGD [B1].

B1 Legacy Shielded ILW / LLW

There are three broad categories of waste packages for legacy ILW / LLW: shielded, unshielded and robust shielded. This waste group deals with the legacy wastes (those that have arisen or will arise from existing facilities) that are packaged in shielded waste containers.

B1.1 Volumes

The total packaged volume of waste in this waste group is estimated to be 92,600 m³. The stored, conditioned and packaged volumes associated with each of the waste containers in this waste group are presented in Table B1. Some of the waste containers have variable levels of internal shielding and the 6 m³ concrete box has standard and high density (SD and HD) variants.

Figure B1 shows the arisings and total packaged volume of the waste group plotted against date. Most of the shielded legacy waste arises as the reactor sites enter their final site clearance phases; the step changes in the arisings profile correspond to individual reactor sites starting (and completing) their final site clearance.

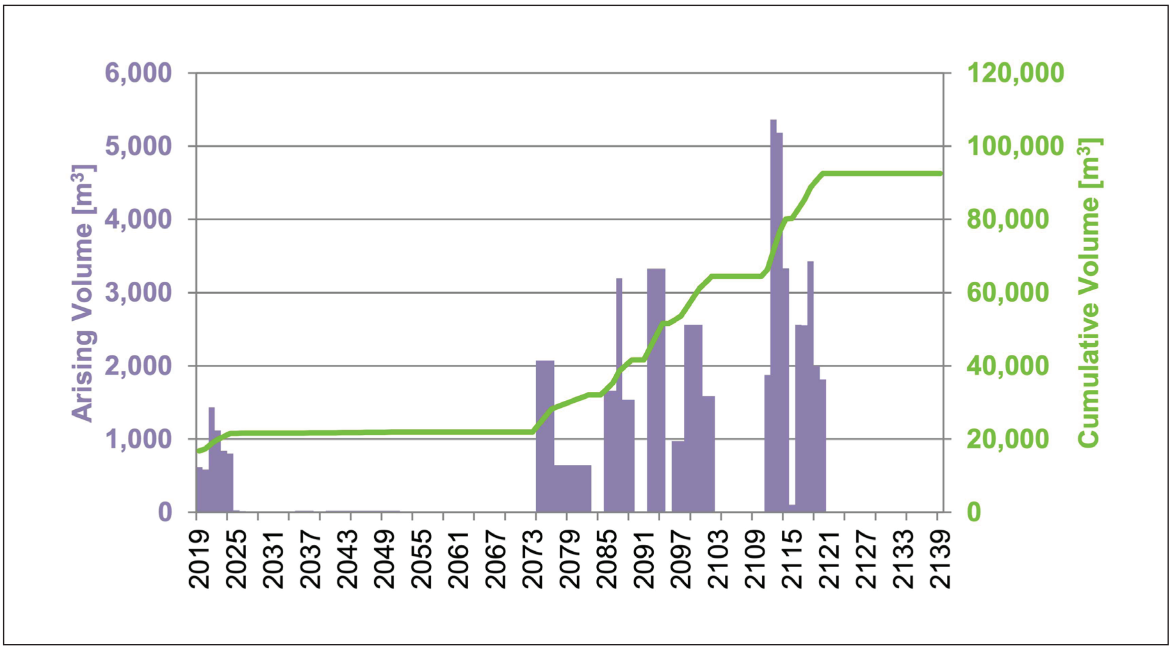
Table B1 - The number of disposal units and volumes associated with each container type in the legacy shielded ILW waste group

Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
2 m box (200 mm concrete)	24.0	149	74.3	245
4 m box (0 mm concrete)	2,420	38,900	45,800	48,500
4 m box (100 mm concrete)	1,220	14,400	17,500	24,500
4 m box (200 mm concrete)	362	1,840	3,950	7,250
6 m^3 box (high density)	213	341	1,200	2,530
6 m^3 box (low density)	806	3,290	4,660	9,550
Total	5,050	59,000	73,200	92,600

B1.2 Disposal units

This waste group has 5,050 disposal units associated with it; Table B1 shows the breakdown by waste container type. The 4 m boxes dominate the number of disposal units.

Figure B1 - The arisings and total packaged volume profiles for legacy shielded waste



B1.3 Radioactivity

The total activity of this waste group at 2040 is estimated to be 15,500 TBq and has risen to 19,400 TBq at 2200. At both 2040 and 2200, the most significant contributor to the total activity of the waste group is Ni-63.

The activity associated with the priority 1 radionuclides at 2040 and 2200 is shown in Table B2. The activity associated with shorter lived radionuclides (eg Co-60) has fallen between 2040 and 2200 due to decay, while the activity associated with longer-lived radionuclides such as C-14 and Cl-36 has increased as more waste, largely graphite from reactor decommissioning, has arisen.

Table B2 - The activity of priority 1 radionuclides in legacy shielded waste

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	64.8	6,400	Cs-135	$4.18\ 10^{-2}$	$4.18\ 10^{-2}$
Cl-36	0.513	26.2	Cs-137	292	7.40
Co-60	1,300	$1.64\ 10^{-3}$	U-233	$5.20\ 10^{-2}$	$5.20\ 10^{-2}$
Se-79	$3.12\ 10^{-4}$	$3.12\ 10^{-4}$	U-235	$3.69\ 10^{-4}$	$3.69\ 10^{-4}$
Kr-85	0.727	$2.36\ 10^{-5}$	U-238	$2.54\ 10^{-2}$	$2.54\ 10^{-2}$
Tc-99	0.137	0.377	Np-237	$3.37\ 10^{-2}$	$3.42\ 10^{-2}$
I-129	$2.90\ 10^{-4}$	$2.90\ 10^{-4}$			

B1.4 Materials

Appendix C2 presents the waste materials data for LHGW. In keeping with the general trend outlined in Section 3.4, the materials comprising the legacy SILW / SLLW waste group are predominantly the “metals” and “other materials”. The most significant contributors are graphite (predominantly from the cores of AGRs and Magnox reactors) and other ferrous metals.

Capping and conditioning materials are predominantly cementitious (although there is a small amount of polymer encapsulation), while the waste package materials are dominated by concrete and stainless steels.

B2 Legacy unshielded ILW / LLW

There are three broad categories of waste packages for legacy ILW / LLW: shielded, unshielded and robust shielded. This waste group deals with the legacy wastes that are packaged in unshielded waste containers.

B2.1 Volumes

The total packaged volume of waste in this waste group is estimated to be 372,000 m^3. Table B3 presents the stored, conditioned and packaged volumes associated with each of the waste containers in this waste group. Some of the waste containers have a number of variants, eg the 500 l drum has two enhanced variants. The conditioned volume of waste associated with a container type can be less than the stored volume if the wastes are compactible (eg for 200 l drums compacted into pucks and grouted into 500 l drums).

Figure B2 shows the arisings and total packaged volume of the waste group plotted against date. Unshielded legacy waste arises continuously because the waste arising as a result of the decommissioning at Sellafield is expected to continue throughout the period that the reactors are in their care and maintenance phase. Spikes in the arisings are associated with specific events (eg 2042 to 2045 a large volume of Magnox pond furniture arises). The broader peak from 2108 to 2111 is predominantly associated with final site clearance wastes at Calder Hall.

Table B3 - The number of disposal units and volumes associated with each container type in the legacy unshielded ILW waste group

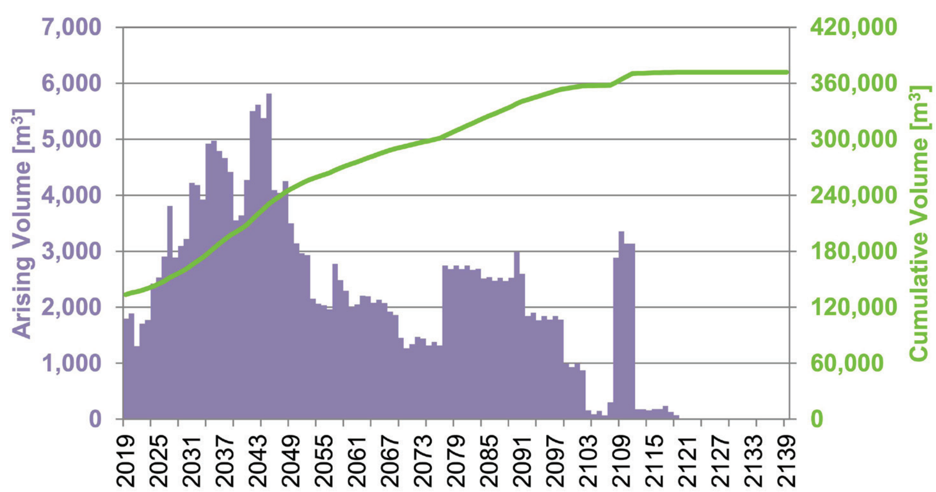
Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
3 m^3 box	8,090	14,900	21,500	26,500
3 m^3 box (square corners)	685	191	1,910	2,470
3 m^3 drum	520	954	1,160	1,360
3 m^3 Sellafield box[36]	35,700	29,100	83,800	118,000
3 m^3 Sellafield Enhanced box	33,900	26,500	74,700	112,000
500 l drum[37]	30,300	53,500	56,400	69,300
Beta/gamma box	1,690	5,870	5,970	7,950
Enhanced 500 l drum (basket)[37, 38]	15,000	33,300	30,200	34,200
Enhanced 500 l drum (pre-cast)[37,38]	207	311	331	473
Total	126,000	165,000	276,000	372,000

B2.2 Disposal units

This waste group has 126,000 disposal units associated with it; Table B2 shows the breakdown by waste container type.

[36] *Note A Sellafield specific example of a 3 m^3 box (corner lifting) box.*
[37] *Four 500 l drums are disposed of together in a stillage, which is defined as a disposal unit.*
[38] *A specific design of 500 l drum.*

Figure B2 - The arisings and total packaged volume profiles for legacy unshielded waste



B2.3 Radioactivity

The total activity of this waste group at 2040 is estimated to be 2,070,000 TBq and even though most of the waste (by volume) arises after this, the activity at 2200 has fallen to 398,000 TBq as a result of radioactive decay. At both 2040 and 2200 the most significant contributor to the total activity of the waste group is Ni-63.

The activity associated with the priority 1 radionuclides at 2040 and 2200 is shown in Table B4. The activity associated with shorter-lived radionuclides (eg Co-60) has fallen between 2040 and 2200, while the activity associated with longer-lived radionuclides such as C-14 and Cl-36 has increased as more waste containing these radionuclides has arisen.

Table B4 - The activity of priority 1 radionuclides in legacy unshielded waste

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	845	1,430	Cs-135	7.23	7.24
Cl-36	2.60	3.90	Cs-137	$2.56\ 10^{5}$	6,570
Co-60	96,100	$8.05\ 10^{-4}$	U-233	0.896	0.991
Se-79	0.466	0.480	U-235	0.597	0.635
Kr-85	877	$2.85\ 10^{-2}$	U-238	20.0	20.8
Tc-99	1,130	1,150	Np-237	117	120
I-129	0.794	0.799			

B2.4 Materials

Appendix C2 presents the waste materials data for LHGW. In keeping with the general trend outlined in Section 3.4, the materials comprising the legacy UILW / ULLW waste group are predominantly the "metals" and "other materials". The most significant contributors are cementitious material, sludges and flocs, other ferrous metals and stainless steel. In absolute terms this waste group has more organic matter than any other, with halogenated plastics, cellulosics, and rubbers the key contributors.

Capping and conditioning materials are predominantly cementitious (although there is a small amount of polymer encapsulation), while the waste package materials are dominated by concrete and stainless steels.

B3 Robust shielded containers

There are three broad categories of waste packages for legacy ILW / LLW: shielded, unshielded and robust shielded. This waste group deals with the legacy wastes that are packaged in robust shielded waste containers.

B3.1 Volumes

The 500 l robust shielded (RS) drum and the 3 m^3 RS box are the only robust shielded ILW containers (RSCs) in the inventory. The total packaged volume of waste in this waste group is estimated to be 2,610 m^3. The stored, conditioned and packaged volumes associated with each of the waste containers in this waste group are presented in Table B5. The waste packagers have the option to include lead shielding within the 500 l RS drums in order to meet the relevant criteria for the dose rate external to the completed waste package. This shielding is provided by lead inserts with thicknesses of up to 120 mm. RS drums with a variety of different thicknesses of lead shielding are used in the inventory for geological disposal.

Figure B3 shows the arisings and total packaged volume of the waste group plotted against date. Only EDF Energy and Magnox use (or are proposing to use) RSCs for the packaging of their wastes. As can be seen in Figure B3, the future arising of wastes that are anticipated to be packaged in RSCs is limited.

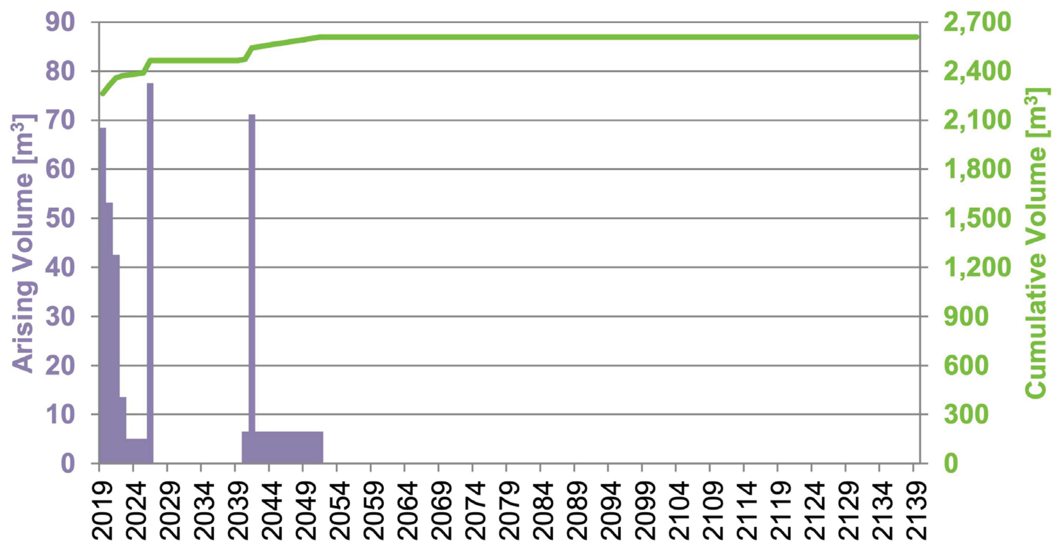
Table B5 - The number of disposal units and volumes associated with each container type in the robust shielded container waste group

Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
3 m^3 RS box	329	941	820	1,790
500 l RS drum (0 mm Pb)	424	181	180	560
500 l RS drum (20 mm Pb)	54	21.6	21.6	71.1
500 l RS drum (40 mm Pb)	59	49.6	18.9	77.9
500 l RS drum (50 mm Pb)	29	4.73	9.72	38.2
500 l RS drum (90 mm Pb)	38	1.84	8.40	49.9
500 l RS drum (120 mm Pb)	15	0.420	2.47	19.6
Total	949	1,200	1,060	2,610

B3.2 Disposal units

This waste group has 949 disposal units associated with it; Table B5 shows the breakdown by waste container type.

Figure B3 - The arisings and total packaged volume profiles for robust shielded containers



B3.3 Radioactivity

The total activity of this waste group at 2040 is estimated to be 4,200 TBq and this has decayed to 3,180 TBq by 2200. **Table B6** shows the activity of the priority 1 radionuclides that are associated with the RSCs at 2040 and 2200. The activity at both 2040 and 2200 is dominated by the contribution from Ni-63.

Table B6 - The activity of priority 1 radionuclides in robust shielded containers

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	3.79	8.88	Cs-135	$1.88\ 10^{-3}$	$1.93\ 10^{-3}$
Cl-36	0.666	0.671	Cs-137	189	5.03
Co-60	16.8	$6.20\ 10^{-6}$	U-233	$1.09\ 10^{-4}$	$1.11\ 10^{-4}$
Se-79	$4.46\ 10^{-5}$	$4.53\ 10^{-5}$	U-235	$1.15\ 10^{-4}$	$1.16\ 10^{-4}$
Kr-85	0.184	$1.39\ 10^{-5}$	U-238	$5.05\ 10^{-3}$	$5.07\ 10^{-3}$
Tc-99	$6.95\ 10^{-2}$	$8.59\ 10^{-2}$	Np-237	$3.31\ 10^{-3}$	$3.44\ 10^{-3}$
I-129	$4.68\ 10^{-4}$	$4.73\ 10^{-4}$			

B3.4 Materials

Appendix C2 presents the waste materials data for LHGW. In keeping with the general trend outlined in **Section 3.4**, the waste materials comprising the RSC waste group are predominantly the “metals” and “other materials”. The most significant contributors are other ferrous metals, graphite and sludges and flocs.

RSCs have no capping or conditioning materials and the packages themselves comprise cast iron and lead.

B4 Depleted, natural and low-enriched uranium (DNLEU)

Most of the UK DNLEU comprises uranic materials produced in the UK thermal reactor fuel cycle: depleted uranium (DU) from fuel enrichment operations and reprocessing of spent fuels. Low-enriched uranium (LEU) arises from a variety of fuel cycle and research activities and makes up a small component of the overall DNLEU inventory. A breakdown of the components of the DNLEU inventory is provided in Table B7.

The components of the DNLEU inventory are:

- Magnox depleted uranium (MDU), which arises from the reprocessing of Magnox fuel
- THORP product uranium (TPU), which arose from the reprocessing of oxide fuel at THORP
- depleted uranium tails from uranium enrichment
- defence DNLEU is uranium that is owned by MOD and does not fall into the HEU category
- miscellaneous DNLEU covers DNLEU from other sources
- uranium tetrafluoride that is owned by NDA

Table B7 - The components of the DNLEU inventory

DNLEU category	Assumed disposed form	Quantity [tU]	Waste container
MDU in 200 l drums	UO_3	23,100	Uranium TDC (2.4 m high)
MDU in 210 l drums	UO_3	10,200	Uranium TDC (2.1 m high)
THORP product uranium	U_3O_8	4,720	500 l drum (DNLEU)
DU tails	U_3O_8	143,000	Uranium TDC (2.3 m high)
Defence DNLEU	UO_3	8,000	Uranium TDC (2.4 m high)
Miscellaneous DNLEU	U_3O_8	2,830	500 l drum (DNLEU)
Uranium tetrafluoride	U_3O_8	230	500 l drum (DNLEU)
Total	n/a	192,000	n/a

B4.1 Volumes

The stored, conditioned and packaged volumes of the DNLEU waste group are presented in Table B8, the vast majority of which is DU tails. Future arisings of DNLEU are predominantly from the enrichment activities at Capenhurst and the reprocessing of Magnox and oxide spent fuels at Sellafield. All these operations are assumed to finish by 2040. This can be seen in Figure B4, which shows the total packaged volume of the DNLEU plotted against the date.

For the MDU and DU tails, the 'stored volume' refers to the volume of the container in which the uranium is currently stored[39], while for the wastes that are assumed to be packaged in 500 l drums, the stored volume refers to the assumed volume of U_3O_8 powder that the uranium would be converted to.

[39] *DV-70s for the DU tails and 200 l drums overpacked in larger (approximately 500 l) drums or 210 l drums for the MDU.*

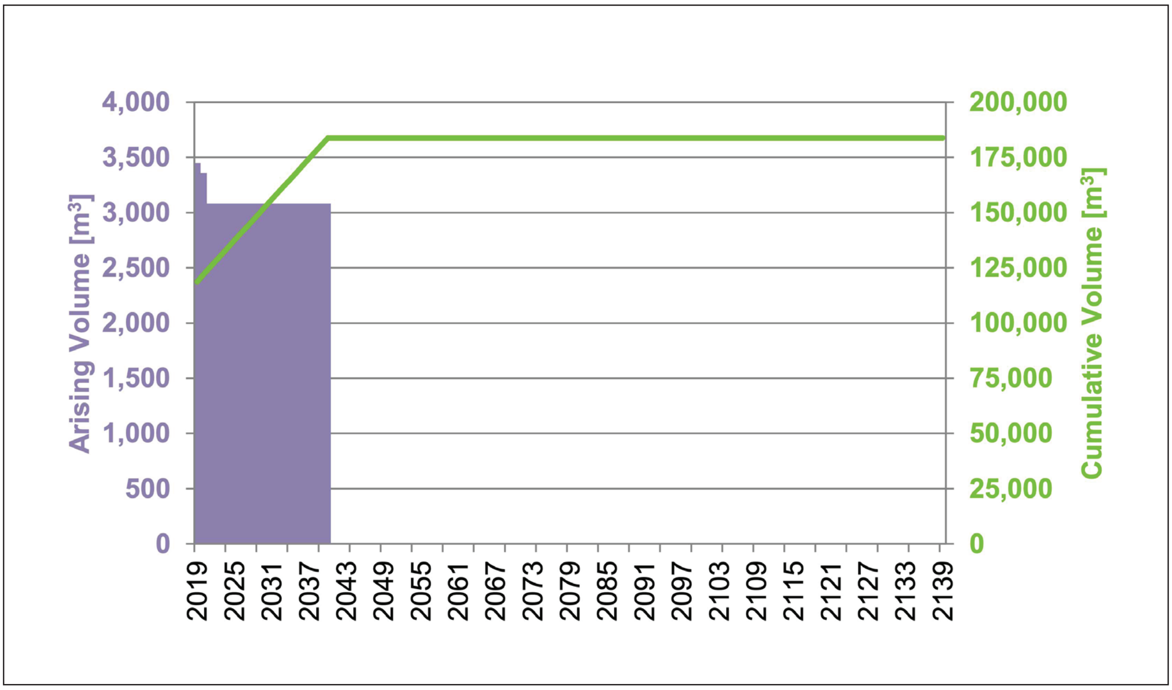
Table B8 - The number of disposal units and volumes associated with each container type in the DNLEU waste group

Waste container	No. disposal units [-]	Volume [m³]		
		Stored	Conditioned	Packaged
500 litre drum (DNLEU)	2,010[40]	1,100	3,780	4,590
Uranium TDC (2.1 m high)	316	4,490	5,940	8,050
Uranium TDC (2.3 m high)	4,110	63,500	81,500	115,000
Uranium TDC (2.4 m high)	1,950	28,100	42,700	56,600
Total	8,380	97,200	134,000	184,000

B4.2 Disposal units

This waste group has 8,380 disposal units associated with it; Table B8 shows the breakdown by waste container type. Transport and disposal containers (TDCs) with three different heights are used.

Figure B4 - The arisings and total packaged volume profiles for DNLEU



[40] *Four 500 l drums are disposed of together in a stillage, which is defined as a disposal unit.*

B4.3 Radioactivity

DNLEU has very low quantities of impurities and is predominantly composed of U-238. At early times, the activity of the DNLEU is dominated by that of the U-238 and its immediate daughters Th-234, half-life 24.1 days, and Pa-234m, half-life 1.17 minutes. Because the half-life of U-238 is very long, the total activity associated with the DNLEU does not change significantly between 2040 and 2200; instead, it remains relatively constant at approximately 9,700 TBq. Of the total activity, 26% is U-238; 26% is Th-234 with the remainder made up from the remaining uranium isotopes. Unlike other waste groups, the activity associated with the DNLEU will increase with time as a result of the ingrowth of further daughters; Figure 10 illustrates this. The activity associated with the priority 1 radionuclides in the DNLEU is shown at 2040 and 2200 in Table B9.

Table B9 - The activity of priority 1 radionuclides in DNLEU

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	$7.18\ 10^{-10}$	$7.04\ 10^{-10}$	Cs-135	$2.53\ 10^{-8}$	$2.53\ 10^{-8}$
Cl-36	0	0	Cs-137	$1.99\ 10^{-3}$	$5.05\ 10^{-5}$
Co-60	0	0	U-233	$5.95\ 10^{-4}$	$2.29\ 10^{-3}$
Se-79	$1.87\ 10^{-9}$	$1.87\ 10^{-9}$	U-235	58.5	59.5
Kr-85	0	0	U-238	2,510	2,560
Tc-99	30.8	30.8	Np-237	2.42	2.44
I-129	$1.69\ 10^{-9}$	$1.69\ 10^{-9}$			

B4.4 Materials

Appendix C2 presents the waste materials data for LHGW. The waste materials comprising the DNLEU waste group are dominated by the heavy metal oxides. The conditioning and capping materials are largely cementitious, while the packages waste containers themselves are stainless steel.

B5 New build shielded ILW

This waste group deals with the wastes arising from an assumed new build programme that are packaged in shielded waste containers. The inventory data for this waste group are based on an assumed 16 GW(e) new build programme.

B5.1 Volumes

The total packaged volume of waste in this waste group is estimated to be 18,900 m^3. The stored, conditioned and packaged volumes associated with each of the waste containers in this waste group are presented in **Table B10**. The waste containers can have variable levels of internal shielding: the concrete drums can have different levels of steel shielding, while the 4 m boxes can include different thicknesses of concrete, though a single thickness is assumed here.

Figure B5 shows the arisings and total packaged volume of the waste group plotted against date. The SILW arises in two blocks: firstly, the operational wastes and then the decommissioning wastes. The reason for the gradual increase and decrease in the arising volumes is that the operation of the reactors is assumed to be staggered (see **Table 1**).

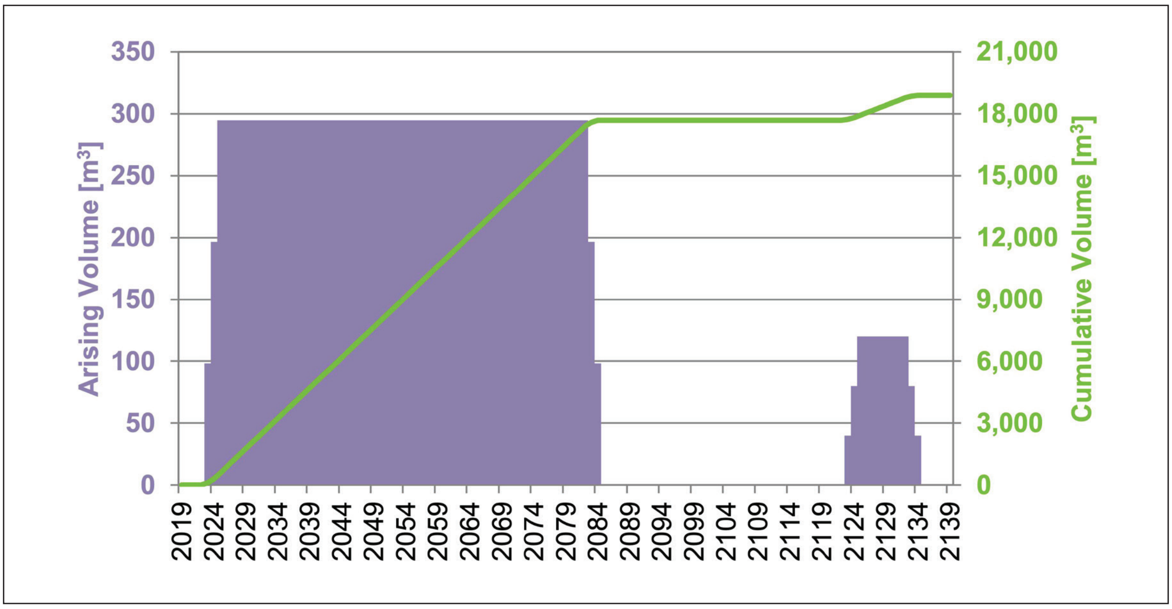
Table B10 - The number of disposal units and volumes associated with each container type in the new build shielded ILW waste group

Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
1 m^3 concrete drum (0 mm steel)	1,800	720	1,590	3,600
1 m^3 concrete drum (40 mm steel)	2,880	1,080	1,790	5,760
1 m^3 concrete drum (70 mm steel)	2,160	900	1,100	4,320
4 m box (100 mm concrete)	60	138	858	1,200
500 l concrete drum (40 mm steel)	3,240	900	942	4,000
Total	10,100	3,740	6,280	18,900

B5.2 Disposal units

This waste group has 10,100 disposal units associated with it; **Table B10** shows the breakdown by waste container type.

Figure B5 - The arisings and total packaged volume profiles for new build shielded waste



B5.3 Radioactivity

The total activity of this waste group at 2040 is estimated to be 197 TBq. At this stage, the new build reactors would be approximately one quarter of the way through their operational lifetimes. By 2200, the reactors would be fully decommissioned and the total activity is estimated to be 154 TBq. The main contributor to the total activity at both 2040 and 2200 is Ni-63.

The activity associated with the priority 1 radionuclides is shown in Table B11. The activity associated with the shorter-lived radionuclides (eg Co-60) has fallen. The activity associated with the longer-lived radionuclides, such as C-14 and Cl-36 is seen to increase as more waste containing these radionuclides has arisen.

Because the concrete drums are used for operational wastes, while the 4 m box is used for decommissioning waste, the concrete drums account for all of the activity at 2040. At 2200, when the decommissioning wastes have arisen, the activity associated with the concrete drums is 92.2 TBq, or 60% of the total.

Table B11 - The activity of priority 1 radionuclides in new build shielded waste

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	1.42	5.44	Cs-135	$1.08\ 10^{-4}$	$4.06\ 10^{-4}$
Cl-36	$3.59\ 10^{-4}$	$1.53\ 10^{-3}$	Cs-137	19.3	3.28
Co-60	46.4	$3.68\ 10^{-4}$	U-233	$1.59\ 10^{-9}$	$1.81\ 10^{-5}$
Se-79	$4.06\ 10^{-4}$	$1.65\ 10^{-3}$	U-235	$4.22\ 10^{-7}$	$1.59\ 10^{-6}$
Kr-85	0	$7.91\ 10^{-5}$	U-238	$1.04\ 10^{-5}$	$3.91\ 10^{-5}$
Tc-99	$1.73\ 10^{-3}$	$1.57\ 10^{-2}$	Np-237	$2.40\ 10^{-5}$	$1.16\ 10^{-4}$
I-129	$2.31\ 10^{-5}$	$8.67\ 10^{-5}$			

B5.4 Materials

Appendix C2 presents the waste materials data for LHGW. The new build SILW waste group has the highest proportion of organics (approximately three eighths by mass). The organics are dominated by organic ion exchange resins, while other significant contributors are other ferrous materials and stainless steel.

Capping and conditioning materials are predominantly cementitious (although there is a small amount of polymer encapsulation), while the waste package container materials are dominated by carbon steel and reinforced concrete.

B6 New build unshielded ILW

There are three broad categories of waste packages for LHGW: shielded, unshielded and robust shielded. This waste group deals with the wastes arising from an assumed new build programme that are packaged in unshielded waste containers. The inventory data for this waste group are based on an assumed 16 GW(e) new build programme.

B6.1 Volumes

The total packaged volume of waste in this waste group is estimated to be 22,100 m^3. The stored, conditioned and packaged volumes associated with each of the waste containers in this waste group are presented in Table B12.

Figure B6 shows the arisings and total packaged volume of the waste group plotted against date. The UILW arises in two blocks: firstly, the operational wastes and then the decommissioning wastes. The reason for the gradual increase and decrease in the arising volumes is that the operation of the reactors is assumed to be staggered (see Table 1).

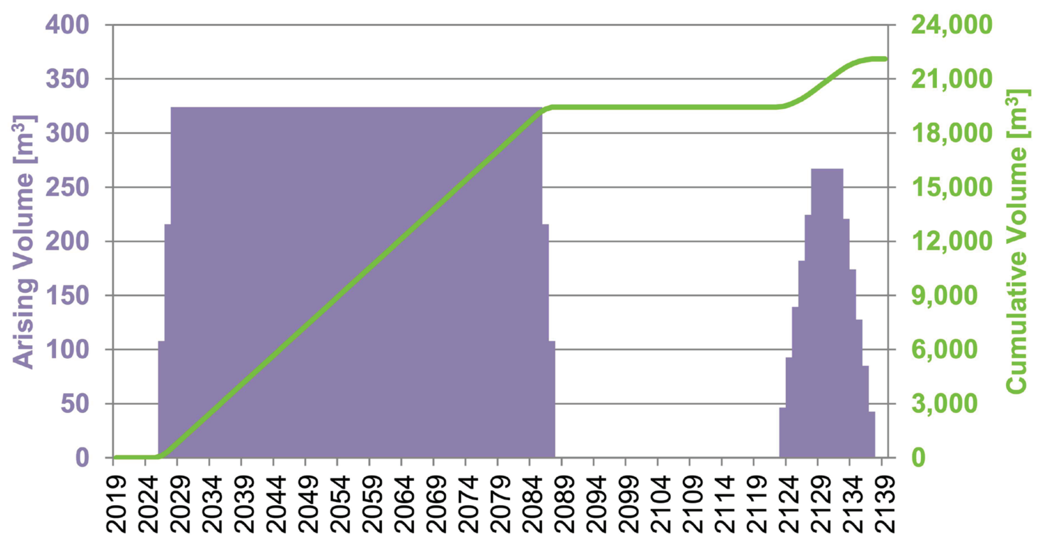
Table B12 - The number of disposal units and volumes associated with each container type in the new build unshielded ILW waste group

Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
3 m^3 box	960	652	2,550	3,140
3 m^3 drum	7,270	4,050	16,200	19,000
Total	8,230	4,700	18,800	22,100

B6.2 Disposal units

This waste group has 8,230 disposal units associated with it; Table B12 shows the breakdown by waste container type.

Figure B6 - The arisings and total packaged volume profiles for new build unshielded waste



B6.3 Radioactivity

The total activity of this waste group at 2040 is estimated to be 875 TBq. At this stage, the new build reactors would be approximately one quarter of the way through their operational lifetimes. By 2200, the reactors would be fully decommissioned and the total activity is estimated to be 793,000 TBq. The main contributor to the total activity at 2040 is Cs-137 (and its short-lived daughter Ba-137m). By 2200, the activity is dominated by Ni-63.

The activity associated with the priority 1 radionuclides is shown in Table B13. The activity associated with the shorter-lived radionuclides (eg Co-60) has fallen. The activity associated with the longer-lived radionuclides, such as C-14 and Cl-36 is seen to increase as more waste containing these radionuclides has arisen.

Table B13 - The activity of priority 1 radionuclides in new build unshielded waste

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	0.697	6,670	Cs-135	$1.92\ 10^{-3}$	$1.58\ 10^{-2}$
Cl-36	$2.16\ 10^{-3}$	0.618	Cs-137	308	101
Co-60	32.9	1.98	U-233	$5.86\ 10^{-7}$	0.114
Se-79	$1.61\ 10^{-4}$	0.428	U-235	$1.39\ 10^{-6}$	$1.07\ 10^{-5}$
Kr-85	0	0.261	U-238	$3.72\ 10^{-5}$	$1.73\ 10^{-4}$
Tc-99	0.123	32.1	Np-237	$6.83\ 10^{-5}$	$6.55\ 10^{-4}$
I-129	$3.57\ 10^{-2}$	0.165			

B6.4 Materials

Appendix C2 presents the waste materials data for LHGW. The new build UILW waste group is approximately 50% metals (stainless steel and other ferrous metals) with equal amounts of organic and inorganic materials (ion exchange resins in both cases).

Capping and conditioning is cementitious, while the waste package container materials are all stainless steels.

B7 High level waste

HLW arises from the reprocessing of Magnox and oxide spent fuels at Sellafield and the post operational clean out of the vitrification plant facilities. These operations are anticipated to finish in 2029 and the arisings of HLW will cease at this point. This can be seen in **Figure B7**, which shows the arisings and total packaged volumes and numbers of packages associated with the HLW.

A proportion of the waste from THORP and the Magnox reprocessing plant at Sellafield results from the reprocessing of overseas spent fuels. All reprocessing contracts with overseas customers that have been signed since 1976 include a provision to return packaged wastes to the country of origin. Waste substitution arrangements are being implemented whereby an additional amount of HLW from reprocessing is returned, which is smaller in volume but equivalent in radiological terms to the customers' ILW and LLW that would otherwise be returned.

B7.1 Volumes

The total packaged volume of waste in this waste group is estimated to be 9,880 m^3. The stored, conditioned and packaged volumes associated with each of the waste containers in this waste group are presented in **Table B14**.

Figure B7 shows the arisings and total packaged volume of the waste group plotted against date. The reduction in volume resulting from return of HLW to overseas reprocessing customers is clearly visible.

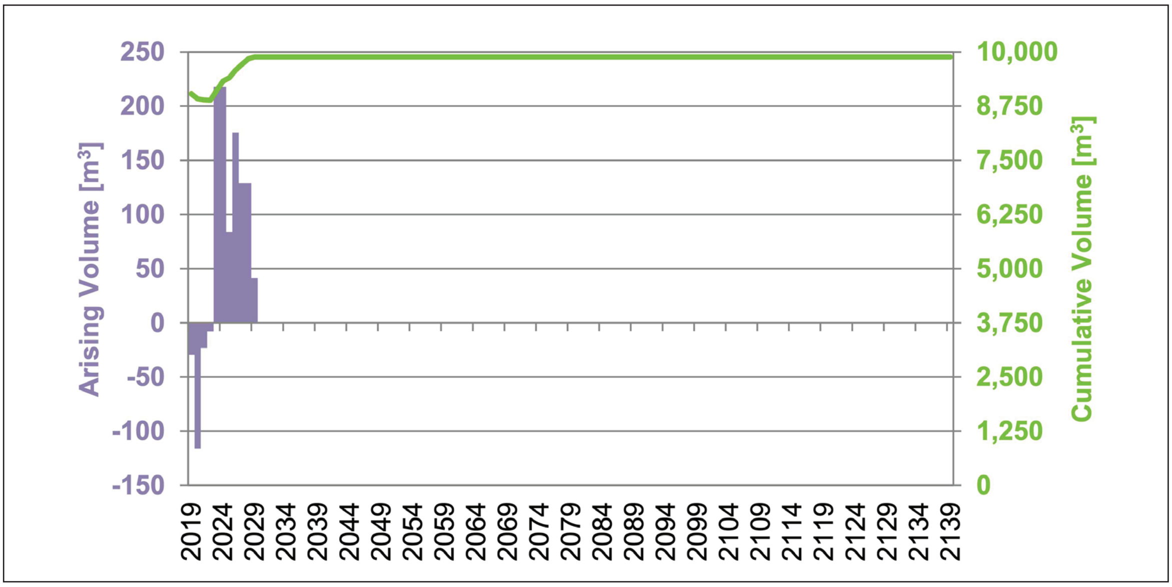
Table B14 - The number of disposal units and volumes associated with each container type in the HLW waste group

Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
Copper Disposal Container HLW	2,550	1,500	1,500	9,880
Total	2,550	1,500	1,500	9,880

B7.2 Disposal units

This waste group has 2,550 disposal units associated with it. All HLW is assumed to be packaged in a copper disposal container.

Figure B7 - The arisings and total packaged volume profiles for HLW



B7.3 Radioactivity

The total activity of this waste group at 2040 is estimated to be 47,100,000 TBq. By 2200, the total activity is estimated to have decayed to 1,460,000 TBq. The key contributor to the activity at both 2040 and 2200 is Cs-137 and its short-lived daughter Ba-137m.

As there are no HLW arisings between 2040 and 2200, the changes in activities are solely a result of decay and ingrowth. The activity associated with the priority 1 radionuclides is shown in Table B15.

Table B15 - The activity of priority 1 radionuclides in HLW

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	1.11	1.09	Cs-135	224	224
Cl-36	1.83	1.83	Cs-137	$1.38\ 10^{7}$	$3.49\ 10^{5}$
Co-60	703	$5.14\ 10^{-7}$	U-233	$6.43\ 10^{-3}$	$4.44\ 10^{-2}$
Se-79	20.6	20.6	U-235	$1.16\ 10^{-3}$	$1.21\ 10^{-3}$
Kr-85	0	0	U-238	$3.01\ 10^{-2}$	$3.01\ 10^{-2}$
Tc-99	3,500	3,500	Np-237	45.0	63.4
I-129	0.108	0.108			

B7.4 Materials

Appendix C3 presents the waste materials data for HHGW. The HLW waste group is dominated by glass (ie the vitrified product) and stainless steel (the waste vitrification plant canisters in which it is currently stored).

The disposal containers are assumed to be predominantly copper and cast iron.

B8 Legacy spent fuels

There are various types of spent fuels that have arisen, or are arising, from legacy commercial and research reactors in the UK and these have different characteristics. These differences are important to RWM's safety cases and data are therefore presented for each of the individual types of spent fuel. The types of spent fuel considered are:

- AGR spent fuel (SF) that is not reprocessed
- Sizewell B SF
- metallic SFs, including fuel that will be recovered from Sellafield legacy ponds (and is assumed to be low burn-up Magnox spent fuel)
- SGHWR SF from Winfrith
- WAGR SF from Windscale
- miscellaneous LWR SF
- PFR SFs

The 2019 IGD contains 5,500 tU of AGR SF, 1,050 tU of Sizewell B PWR SF, 723 tU of metallic SF, 68 tU SGHWR SF, 20.8 tU WAGR SF, 66 tU Miscellaneous LWR SF and 10 tHM of PFR SF. The legacy SF waste group also contains irradiated submarine fuel, which has not been quantified, or classified as waste (see **Section 2.3.2**).

B8.1 Volumes

When all the legacy SFs have been packaged for disposal, they are estimated to have a packaged volume of 17,000 m^3. The future arisings come from the operations of AGR stations and Sizewell B PWR. These reactors will all be shut down by 2035 and the arisings of legacy SFs will cease at this point. This can be seen in **Figure B8**, which shows the arisings and total packaged volume of the SFs plotted against date. **Table B16** shows the packaged volumes and number of disposal units associated with the legacy SFs.

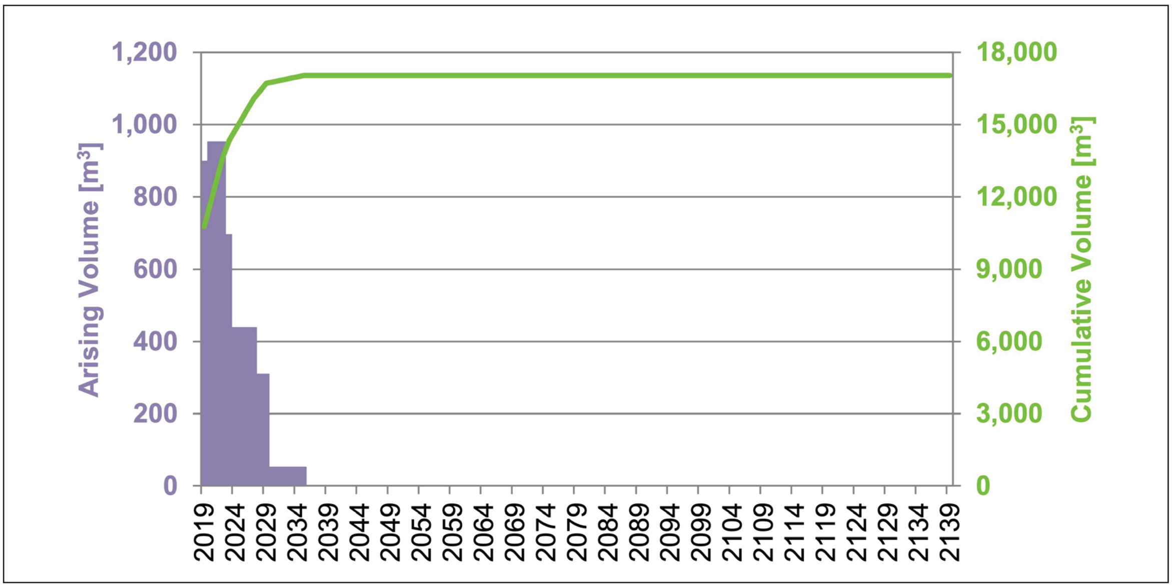
Table B16 - The number of disposal units and volumes associated with each container type in the legacy spent fuels waste group

Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
Copper Disposal Container AGR	2,710	2,400	2,400	11,400
Copper Disposal Container Magnox	817	976	976	3,320
Copper Disposal Container PFR	18.2	10.9	10.9	48.7
Copper Disposal Container PWR	608	452	452	2,290
Irradiated submarine fuel	Not quantified			
Total	4,160	3,840	3,840	17,000

B8.2 Disposal units

This waste group has 4,160 disposal units associated with it. All legacy spent fuels are assumed to be packaged in copper disposal containers. For PWR SF, four assemblies are assumed to be disposed of in a disposal container, while for PFR SF it is seven assemblies in a disposal container. Twenty-six Magnox SF elements are assumed to be packaged into a canister, with three canisters in a disposal container. It is envisaged that the AGR SF assemblies will be dismantled first. The graphite sleeves, support grids, braces, etc will be processed separately as ILW; the remaining fuel pins will be consolidated into bundles, with each bundle being contained within a slotted can. It is assumed that a total of sixteen slotted cans (equivalent to the fuel pins from 48 AGR fuel elements) will be packaged in a single disposal container. The SGHWR SF and WAGR SF are assumed to be packaged in a disposal container with the same dimensions as the AGR SF disposal container. A PWR SF disposal container is assumed to be used for the miscellaneous LWR SF.

Figure B8 - The arisings and total packaged volume profiles for legacy spent fuels



B8.3 Radioactivity

The activity of this waste group at 2040 is estimated to be 67,400,000 TBq. By 2200, the activity is estimated to be 2,780,000 TBq. The quantity of AGR SF is greater than that of the other fuel types and it would therefore be expected that it has the highest activity associated with it; this is seen to be the case in **Table B17**. The biggest contributor to the total activity at 2040 is Cs-137 (and its short-lived daughter Ba-137m). At 2200, the biggest contributor to the total activity is Am-241.

The activities of the priority 1 radionuclides are presented in **Table B18**. Since all the legacy spent fuels have arisen by 2035, any increases in radionuclide activities will be a result of ingrowth (eg Np-237 is a daughter of Am-241, which is itself a daughter of Pu-241).

Table B17 - The activity associated with each of the legacy SFs at 2040 and 2200

Fuel type	Activity at 2040 [TBq]	Activity at 2200 [TBq]
AGR SF	$4.97\ 10^{7}$	$2.06\ 10^{6}$
Magnox SF	$3.21\ 10^{5}$	$2.40\ 10^{4}$
PWR SF	$1.62\ 10^{7}$	$6.09\ 10^{5}$
PFR SF	$3.05\ 10^{5}$	$3.79\ 10^{4}$
Windscale (WAGR) SF	$4.40\ 10^{4}$	$2.97\ 10^{3}$
Winfrith (SGHWR) SF	$3.94\ 10^{5}$	$2.36\ 10^{4}$
Misc. LWR SF	$4.93\ 10^{5}$	$2.55\ 10^{4}$
Irradiated submarine fuel	Not quantified	

Table B18 - The activity of priority 1 radionuclides in legacy spent fuels

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	889	872	Cs-135	157	157
Cl-36	3.58	3.58	Cs-137	$1.62\ 10^{7}$	$4.10\ 10^{5}$
Co-60	$2.50\ 10^{5}$	$1.83\ 10^{-4}$	U-233	0.532	0.582
Se-79	15.9	15.9	U-235	3.98	3.99
Kr-85	$6.11\ 10^{5}$	19.8	U-238	87.6	87.6
Tc-99	2,040	2,040	Np-237	56.0	88.9
I-129	8.00	8.00			

B8.4 Materials

Appendix C3 presents the waste materials data for HHGW. The legacy SF waste group is dominated by fuel materials (heavy metal oxide and uranium) and cladding materials (stainless steel, Zircaloy and Magnox).

The containers are assumed to be predominantly copper and cast iron.

B9 New build spent fuel

As the spent fuels from the UK EPR and AP1000 are similar in terms of their size (it is assumed that a common disposal container will be used for the two) and their burn-ups are assumed to be the same (65 GWd/tU), the two are included together in this waste group and are not discussed separately. The two different spent fuels are, however, considered as separate waste streams.

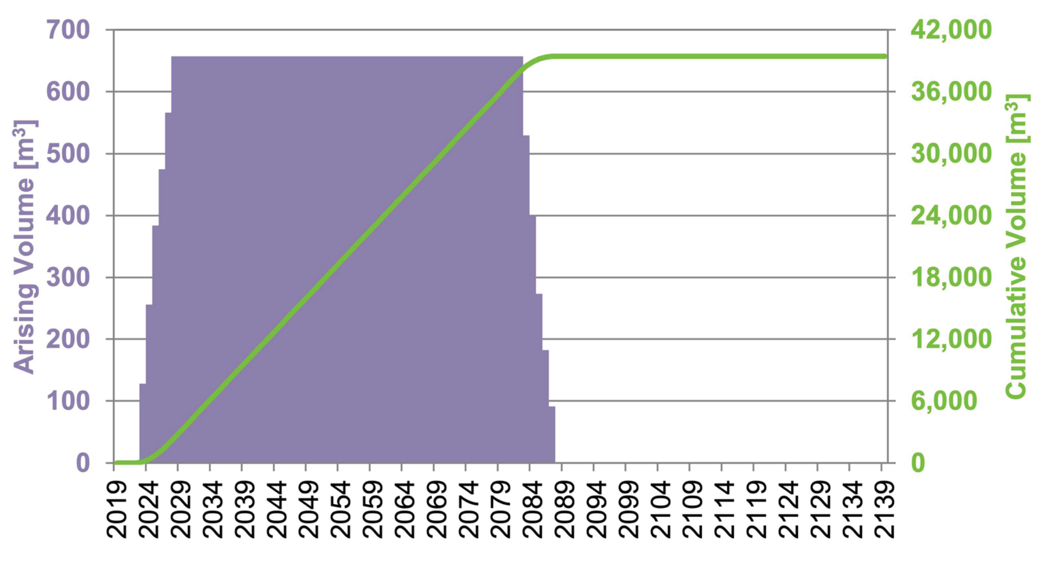
B9.1 Volumes

By the time that the assumed 16 GW(e) new build programme has finished operating, it is estimated that the total packaged volume[41] will be 39,400 m^3. **Table B19** shows that there will be no conditioning for the SFs, while **Figure B9** shows the arisings and total packaged volume profiles for the new build SFs. The gradual increase and decrease in arisings is associated with the assumed staggered start for the new build reactors (see **Table 1**) and the different step sizes in the arisings profile are associated with the different reactor types.

Table B19 - The number of disposal units and volumes associated with each container type in the new build spent fuel waste group

Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
Copper Disposal Container NB SF	8,940	5,890	5,890	39,400
Copper Disposal Container NB SF	8,940	5,890	5,890	39,400

Figure B9 - The arisings and total packaged volume profiles for new build spent fuels



[41] *It is noted that this is based on the assumption that the 16 GW(e) will comprise 6 UK EPRs and 6 AP1000s. Potential changes to the size and composition of a new build programme are considered in an alternative scenario [8, 5].*

B9.2 Disposal units

There are 8,940 disposal units associated with this waste group. For UK EPR and AP1000 spent fuels, three assemblies are assumed to be disposed of in a single disposal container.

B9.3 Radioactivity

At 2040, the activity associated with the new build spent fuels has been estimated to be 127,000,000 TBq; by 2200, this has fallen to 19,000,000 TBq as a result of the decay of the short-lived radionuclides such as Co-60 and Cs-137. Although the activity has fallen significantly in this period, **Figure B9** shows that approximately 75% of the waste arises after 2040. At both 2040 and 2200, the biggest contributor to the total activity is Cs-137 (and its short-lived daughter Ba-137m).

The activities associated with the priority 1 radionuclides are presented in **Table B20**. As would be expected, the longer lived radionuclides (such as C-14) show an increase by a factor of approximately three, consistent with around 25% of the waste having arisen by 2040.

Table B20 - The activity of priority 1 radionuclides in new build spent fuels

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	536	2,150	Cs-135	126	515
Cl-36	18.6	71.7	Cs-137	$2.21\ 10^{7}$	$4.13\ 10^{6}$
Co-60	$2.71\ 10^{5}$	0.114	U-233	$2.62\ 10^{-2}$	0.381
Se-79	15.1	61.6	U-235	1.55	6.24
Kr-85	$1.23\ 10^{6}$	$1.19\ 10^{3}$	U-238	39.9	163
Tc-99	3,170	12,900	Np-237	93.5	517
I-129	7.72	31.3			

B9.4 Materials

Appendix C3 presents the waste materials data for HHGW. The new build SF waste group is dominated by heavy metal oxide (ie the fuel) and zircaloy

The containers are assumed to be copper and cast iron.

B10 Mixed oxide spent fuel

The assumptions regarding MOX are detailed in **Appendix A3**. It is assumed that the MOX is irradiated to 50 GWd/tU and that the unirradiated fuel contains 8% plutonium. The MOX is assumed to be packaged with one SF assembly in a disposal container; this leads to the package numbers and volumes presented in **Table B21**.

B10.1 Volumes

The MOX SF is assumed to arise evenly over a 40 year period starting in 2035, and this can be seen in **Figure B10**. The packaged volume of the waste is assumed to be 11,400 m^3. As can be seen in **Table B21**, the MOX SF is not conditioned.

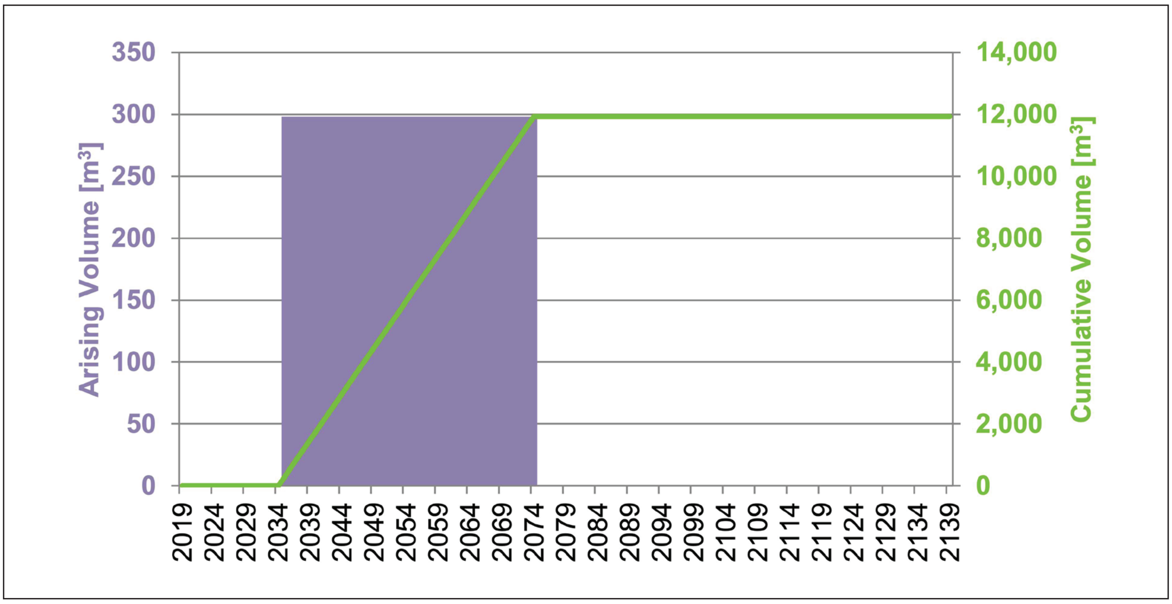
Table B21 - The number of disposal units and volumes associated with each container type in the mixed oxide spent fuel waste group

Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
Copper Disposal Container MOX	2,710	594	594	11,900
Total	2,710	594	594	11,900

B10.2 Disposal units

There are 2,710 disposal units associated with this waste group.

Figure B10 - The arisings and total packaged volume profiles for MOX spent fuel



B10.3 Radioactivity

The total activity of the MOX SF at 2040 has been estimated to be 14,900,000 TBq. However, only one eighth of the MOX SF has arisen by this point. Despite the arisings, the activity by 2200 has fallen to 3,700,000 TBq. At 2040 the biggest contributor to the total activity is Pu-241; by 2200, the biggest contributor is its daughter Am-241.

The activities of the priority 1 radionuclides are shown in Table B22. The activities of shorter-lived radionuclides, such as Co-60 and Cs-137 have fallen, while the activities of the longer-lived radionuclides, such has U-238 and C-14, have increased by a factor of approximately seven, consistent with the increase in the volume of SF between 2040 and 2200. The activity of Np-237 has increased by a very large factor (nearly 100); this is because of its ingrowth as a daughter of Am-241, which is itself a daughter of Pu-241.

Table B22 - The activity of priority 1 radionuclides in MOX spent fuel

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	29.8	234	Cs-135	10.5	83.8
Cl-36	0.192	1.54	Cs-137	$9.96\ 10^{5}$	$3.12\ 10^{5}$
Co-60	$1.25\ 10^{5}$	$1.89\ 10^{-2}$	U-233	$3.63\ 10^{-2}$	0.318
Se-79	0.535	4.28	U-235	$1.68\ 10^{-2}$	0.147
Kr-85	$3.97\ 10^{4}$	41.4	U-238	2.00	16.0
Tc-99	130	1,040	Np-237	0.929	88.3
I-129	0.410	3.28			

B10.4 Materials

Appendix C3 presents the waste materials data for HHGW. The MOX SF waste group is dominated by heavy metal oxide (ie the fuel) and zircaloy (ie the cladding).

The containers are assumed to be copper and cast iron.

B11 Highly enriched uranium

B11.1 Volumes

The 2019 IGD includes 22.9 tU HEU, the same as included in the 2016 IGD. Table B23 shows the volume of the HEU and the number of disposal containers. The packaged volume of HEU in the 2019 IGD is 2,470 m^3; this is based on the can-in-canister approach to packaging. No further arisings of HEU are anticipated and therefore no plot of arisings is presented.

Table B23 - The number of disposal units and volumes associated with each container type in the highly enriched uranium waste group

Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
Copper Disposal Container Pu/HEU	780	2.37	694	2,470
Total	780	2.37	694	2,470

B11.2 Disposal units

There are 780 disposal units associated with this waste group; this is based on the can-in-canister approach to packaging.

B11.3 Radioactivity

The total activity of the HEU at 2040 is 53.6 TBq, and this has risen to 53.7 TBq at 2200 as a result of the ingrowth of daughter radionuclides. The dominant contribution to the activity is U-234 (50.0 TBq), which is a shorter lived (half-life 2.46 10^5 years) isotope of uranium than either U-235 (7.04 10^8 years) or U-238 (4.47 10^9 years). HEU has very few impurities and as a result, the activity at 2040 results almost entirely from uranium isotopes. Similar to the DNLEU, an increase in activity is observed with time, resulting from the ingrowth of the daughters.

B11.4 Materials

Appendix C3 presents the waste materials data for HHGW. The HEU waste group is dominated by stainless steel (ie cans / canister containing the HEU) and glass (ie the encapsulating matrix). Heavy metal oxide is only a small part of the mass.

The containers are assumed to be copper and cast iron.

B12 Plutonium

B12.1 Volumes

The 2019 IGD reports 5.75 t of plutonium (that plutonium which is not suitable for the manufacture of MOX fuel to be irradiated in a reactor). The volume associated with this plutonium is presented in **Table B24**. The total packaged volume is estimated to be 620 m^3; this is based on the can-in-canister approach to packaging. It is assumed that there will be no future arisings of Pu and so no plot of arisings is presented.

Table B24 - The number of disposal units and volumes associated with each container type in the plutonium waste group

Waste container	No. disposal units [-]	Volume [m^3]		
		Stored	Conditioned	Packaged
Copper Disposal Container Pu/HEU	196	0.567	174	620
Total	196	0.567	174	620

B12.2 Disposal units

There are 196 disposal units associated with this waste group.

B12.3 Radioactivity

The total activity of the plutonium at 2040 has been estimated to be 62,000 TBq and this has fallen to 43,700 TBq by 2200. The biggest contributor to the total activity at both 2040 and 2200 is Am-241 which is the daughter of Pu-241. The activities of the priority 1 radionuclides are presented in **Table B25**.

Table B25 - The activity of priority 1 radionuclides in the plutonium waste group

Radionuclide	Activity [TBq]		Radionuclide	Activity [TBq]	
	At 2040	At 2200		At 2040	At 2200
C-14	$6.24\ 10^{-8}$	$6.12\ 10^{-8}$	Cs-135	$3.05\ 10^{-8}$	$3.05\ 10^{-8}$
Cl-36	$2.39\ 10^{-10}$	$2.39\ 10^{-10}$	Cs-137	$4.99\ 10^{-4}$	$1.26\ 10^{-5}$
Co-60	$3.48\ 10^{-10}$	$2.54\ 10^{-19}$	U-233	$5.47\ 10^{-5}$	$6.26\ 10^{-4}$
Se-79	$1.31\ 10^{-8}$	$1.31\ 10^{-8}$	U-235	$8.30\ 10^{-4}$	$2.48\ 10^{-3}$
Kr-85	$1.61\ 10^{-6}$	$5.22\ 10^{-11}$	U-238	$3.47\ 10^{-6}$	$3.54\ 10^{-6}$
Tc-99	$4.51\ 10^{-7}$	$4.51\ 10^{-7}$	Np-237	0.377	1.23
I-129	$9.51\ 10^{-10}$	$9.51\ 10^{-10}$			

B12.4 Materials

Appendix C3 presents the waste materials data for HHGW. The plutonium waste group is dominated by stainless steel (ie cans / canister containing the Pu) and glass (ie the encapsulating matrix). Heavy metal oxide is only a small part of the mass.

The containers are assumed to be copper and cast iron.

Appendix B References

B1 Radioactive Waste Management, Geological Disposal: *The 2013 Derived inventory*, DSSC/403/01, December 2016

Appendix C - Material summary tables

Appendix C presents materials data as follows:

- Table C1: The number of disposal units, packaged volume and activity in each waste group
- Table C2: The number of waste packages, disposal units, conditioned and packaged volumes for each waste container
- Table C3: The metals in the LHGW bulk materials (priority materials are highlighted)
- Table C4: The organics in the LHGW bulk materials (priority materials are highlighted)
- Table C5: The inorganics in the LHGW bulk materials (priority materials are highlighted)
- Table C6: The bulk materials in LHGW conditioning materials
- Table C7: The bulk materials in LHGW capping materials
- Table C8: The bulk metals in LHGW containers (priority materials are highlighted)
- Table C9: The other bulk materials in LHGW containers
- Table C10: The HHGW bulk metals (priority materials are highlighted)
- Table C11: The HHGW bulk other materials
- Table C12: The bulk materials in HHGW containers (priority materials are highlighted)

C1 Waste group disposal units, volumes and activities

Table C1 - The number of disposal units, packaged volume and activity in each waste group

Waste Group	No. disposal units [-]	Packaged volume [m^3]	Activity at 2200 [TBq]
Legacy SILW / SLLW	5,050	92,600	19,400
Legacy UILW / ULLW	126,000	372,000	398,000
RSCs	949	2,610	3,180
DNLEU	8,380	184,000	9,800
NB SILW	10,100	18,900	154
NB UILW	8,230	22,100	793,000
HLW	2,550	9,880	1,460,000
Legacy SF	4,160	17,000	2,780,000
NB SF	8,940	39,400	19,000,000
MOX SF	2,710	11,900	3,700,000
HEU	780	2,470	53.7
Pu	196	620	43,700
Total	178,000	773,000	28,200,000

Table C2 - The number of waste packages, disposal units, conditioned and packaged volumes for each waste container

Waste Container	No. packages [-]	No. disposal units [-]	Conditioned volume [m^3]	Packaged volume [m^3]
Legacy SILW / SLLW				
2m box (200mm concrete)	24	24	74	245
4m box (0mm concrete)	2,420	2,420	45,800	48,500
4m box (100mm concrete)	1,220	1,220	17,500	24,500
4m box (200mm concrete)	362	362	3,950	7,250
6 m^3 box (high density)	213	213	1,200	2,530
6 m^3 box (low density)	806	806	4,660	9,550
Total	5,050	5,050	73,200	92,600

UILW / ULLW				
3 m^3 box	8,090	8,090	21,500	26,500
3 m^3 box (square corners)	685	685	1,910	2,470
3 m^3 drum	520	520	1,160	1,360
3 m^3 Sellafield box	35,700	35,700	83,800	118,000
3 m^3 Sellafield Enhanced box	33,900	33,900	74,700	112,000
500 litre drum	121,000	30,300	56,400	69,300
Beta/gamma box	1,690	1,690	5,970	7,950
Enhanced 500 litre drum (basket)	59,900	15,000	30,200	34,200
Enhanced 500 litre drum (pre-cast)	828	207	331	473
Total	263,000	126,000	276,000	372,000

RSCs				
DCIC Cubical (Type 6)	329	329	820	1,790
500 l RS drum (0 mm Pb)	424	424	180	560
500 l RS drum (20 mm Pb)	54	54	22	71
500 l RS drum (40 mm Pb)	59	59	19	78
500 l RS drum (50 mm Pb)	29	29	9.72	38.2
500 l RS drum (90 mm Pb)	38	38	8.40	49.9
500 l RS drum (120 mm Pb)	15	5	2.47	19.6
Total	949	949	1,060	2,610

Waste Container	No. packages [-]	No. disposal units [-]	Conditioned volume [m³]	Packaged volume [m³]
DNLEU				
500 litre drum (DNLEU)	8,040	2,010	3,780	4,590
Uranium TDC (2.1m ht)	316	316	5,940	8,050
Uranium TDC (2.3m ht)	4,110	4,110	81,500	115,000
Uranium TDC (2.4m ht)	1,950	1,950	42,700	56,600
Total	14,400	8,380	134,000	184,000

New Build SILW				
1 m^3 concrete drum (0 mm steel)	1,800	1,800	1,590	3,600
1 m^3 concrete drum (40 mm steel)	2,880	2,880	1,790	5,760
1 m^3 concrete drum (70 mm steel)	2,160	2,160	1,100	4,320
4 m box (100mm concrete)	60	60	858	1,200
500 l concrete drum (40 mm steel)	3,240	3,240	942	4,000
Total	10,100	10,100	6,280	18,900

New build UILW				
3 m^3 box	960	960	2,550	3,140
3 m^3 drum	7,270	7,270	16,200	19,000
Total	8,230	8,230	18,800	22,100

HLW				
Copper Disposal Container HLW	2,550	2,550	1,500	9,880

Legacy SF				
AGR SF Disposal Container	2,710	2,710	2,400	11,400
Magnox SF Disposal Container	817	817	976	3,320
PFR SF Disposal Container	19	19	10.9	48.7
PWR SF Disposal Container	608	608	452	2,290
Total	4,160	4,160	3,840	17,000

New Build SF				
NB SF Disposal Container	8,940	8,940	5,890	39,400

MOX SF				
MOX Disposal Container	2,710	2,710	594	11,900

HEU				
Pu / HEU Disposal Container	779	779	694	2,470

Plutonium				
Pu / HEU Disposal Container	196	196	174	620

C2 LHGW waste group materials

Table C3 - The metals in the LHGW bulk materials (priority materials are highlighted)

	Material mass [t]					
Material	SILW	UILW	RSC	DNLEU	NB SILW	NB UILW
Aluminium (and alloys)	24.3	1,000	1.09	0	0	0
Beryllium	13.5	14.9	0	0	0	0
Cadmium	0.186	13.8	0	0	0	0
Copper (and alloys)	15.6	289	0.0799	0	0	0
Lead	3.10	751	0.143	0	0	0
Magnox	342	6,180	16.1	0	0	0
Mercury	0	3.97	0	0	0	0
Nickel	23.5	77.7	3.32	0	0	0
Other ferrous metals	11,700	17,800	354	13,400	1,080	1,840
Stainless Steel	3,400	23,000	122	4,220	517	2,290
Uranium	0.0820	1,090	0	0	0	0
Zinc	0	42.9	0.0945	0	0	0
Zircaloy	41.2	1,280	4.94	0	0	0
Iron	3,100	87.6	0	0	0	0
Other Metals	13.6	194	0.481	0	0	0
Total metals	18,600	51,800	503	17,600	1,600	4,130

Table C4 - The organics in the LHGW bulk materials (priority materials are highlighted)

	Material mass [t]					
Material	SILW	UILW	RSC	DNLEU	NB SILW	NB UILW
Cellulosics	16.2	1,030	1.45	0	15.8	0
Halogenated Plastics	3.44	3,070	2.04	0	25.9	0
Non-Halogenated Plastics Total	299	962	5.32	92.9	116	2.72
Ion Exchange Resins	146	108	103	0	1,080	2,030
Rubbers	0.897	1,090	1.36	0	6.57	0
Hydrocarbons	1.49	38.6	5.25	0	0	0
Other Organics	2.67	98.1	5.85	0	7.20	0
Total organics	469	6,400	124	92.9	1,250	2,030

Table C5 - The inorganics in the LHGW bulk materials (priority materials are highlighted)

	Material mass [t]					
Material	SILW	UILW	RSC	DNLEU	NB SILW	NB UILW
Asbestos	0.300	64.5	1.14	0	0	0
Graphite	57,100	13,400	245	0	0	0
Aqueous liquids	234	9,250	52.1	0	37.0	2.66
Cementitious material	1,690	55,700	5.21	0	0	0
Desiccants	0.0820	628	31.6	0	0	0
Glass/Ceramics	21.3	437	0.421	0	12.6	0
Heavy Metal Oxide	0.0	0	0	227,000	0	0
Inorganic Ion Exchange Resins	170	2,940	17.1	0	0	2,030
Rubble	106	793	167	0	1.44	0
Sand	63.9	301	81.0	0	0	0
Sludges and flocs	86.1	20,200	185	0	432	0
Soil	0.0	0.526	0.264	0	0	0
Other inorganics	0.444	132	2.16	0	0	0
Total inorganics	59,400	104,000	788	227,000	483	2,030

Table C6 - The bulk materials in LHGW conditioning materials

	Material mass [t]					
Material[42]	SILW	UILW	RSC	DNLEU	NB SILW	NB UILW
BFS/PFA[43]	13,300	146,000	0	34,400	1,810	15,800
Ordinary Portland cement (OPC)	4,420	43,000	0	12,700	532	2,160
Polymer	324	106	0	0	849	0
S/Steel	0	0	0	80.4	0	0
Water	7,230	77,200	0	19,300	955	7,340
Total conditioning materials	25,200	266,000	0	66,500	4,140	25,300

Table C7 - The bulk materials in LHGW capping materials

	Material mass [t]					
Material	SILW	UILW	RSC	DNLEU	NB SILW	NB UILW
OPC	0	7,980	0	154	0	531
PFA	0	23,900	0	462	0	1,590
Water	0	5,580	0	108	0	372
Iron Shot Concrete	21,000	0	0	0	271	0
Total	21,000	37,500	0	724	271	2,500

[42] *All cementitious materials are assumed to contain 0.5 wt% superplasticiser.*
[43] *Blast furnace slag / pulverised fuel ash.*

Table C8 - The bulk metals in LHGW containers (priority materials are highlighted)

	Material mass [t]					
Material	SILW	UILW	RSC	DNLEU	NB SILW	NB UILW
Lead	0	0	336	0	0	0
Stainless steel[44]	20,100	106,000	0	42,500	300	3,630
Carbon steel	713	3,380	0	0	13,300	0
Cast iron	0	0	9,570	0	0	0
Total	20,800	110,000	9,910	42,500	13,600	3,630

Table C9 - The other bulk materials in LHGW containers

	Material mass [t]					
Material	SILW	UILW	RSC	DNLEU	NB SILW	NB UILW
Concrete[42]	21,900	58,900	0	0	750	0
Magnetite concrete	5,390	0	0	0	0	0
Reinforced concrete	10,700	0	0	0	22,700	0
Total	38,000	58,900	0	0	23,500	0

[44] *For UILW / ULLW there is an additional mass of 31,900t and 1,410t for DNLEU due to 4 500l drums being disposed of together in a stainless steel stillage of mass 0.7t.*

C3 HHGW waste group materials

Table C10 - The HHGW bulk metals (priority materials are highlighted)

	Material mass [t][45]					
Material	HLW	Legacy SF[46]	NB SF	MOX SF	HEU	Pu
Magnox	0	130	0	0	0	0
Stainless Steel	653	1,620	391	39.5	1,820	458
Uranium	0	723	0	0	0	0
Zircaloy	0	286	4,280	438	0	0
Nickel	20.6	19.1	126	11.8	0	0
Total metals	674	2,780	4,800	490	1,820	458

Table C11 - The HHGW bulk other materials

	Material mass [t][45]					
Material	HLW	Legacy SF	NB SF	MOX SF	HEU	Pu
Glass/Ceramics	3,030	42.9	15.6	1.61	1,220	306
Heavy Metal Oxide	0	7,620	16,200	1,660	26.0	6.52
Total inorganics	3,030	7,660	16,200	1,660	1,250	312

[45] *For HLW, HEU and plutonium, the mass includes the glass conditioning matrix and the stainless-steel container. SFs are packaged without any conditioning matrix.*
[46] *WAGR SF consists of stainless steel clad or beryllium clad fuel pins, for the 2019 IGD they have all been assumed to be stainless steel clad.*

Table C12 - The bulk materials in HHGW containers (priority materials are highlighted)

	Material mass [t]					
Material	HLW	Legacy SF	NB SF	MOX SF	HEU	Pu
Copper	18,900	32,300	73,600	22,300	4,850	1,220
Carbon steel	2,710	830	0	0	0	0
Cast Iron	40,200	65,800	178,000	63,100	8,610	2,160
Total	61,900	98,900	251,000	85,400	13,500	3,380

Appendix D - Materials from GDF construction and operating equipment

Table D1 - Estimated material masses associated with GDF construction in a higher strength host rock[47]

	Material mass [t]								
Material	HHGW disposal tunnel	UILW vault	RSILW[48] vault	NB SILW vault	SILW vault	LLW vault	DNLEU vault	Shaft & drift	Common service areas
Aluminium (and alloys)	0	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	0	0
Bentonite	26,800	0	0	0	0	0	0	0	0
Cementitious material	1,940	91,500	24,100	89,600	77,900	77,900	77,900	103,000	19,200
Copper (and alloys)	0	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	0	0
Glass / ceramic Total	0	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	0	0
Halogenated Plastics	0	0.157	0.157	0.157	0.157	0.157	0.157	0	0
Other ferrous metals	0	42.4	42.4	42.4	23.8	16.3	16.3	0	0
Other organics	0.457	0.905	0.802	0.802	0.802	0.802	0.802	0	7.41
Stainless steel	10.5	41.5	40.5	41.1	33.3	33.3	33.3	506	166
Zinc	0	0.168	0.168	0.168	0.168	0	0	0	0

[47] *For For tunnels and vaults, the masses are presented for a single unit; they need to be multiplied by the appropriate number of tunnels / vaults. The 'shaft and drift' and 'common service areas' are an estimated total for the GDF*
[48] *Robust shielded ILW.*

Table D2 - Estimated material masses associated with GDF construction in a lower strength sedimentary host rock[47]

	Material mass [t]								
Material	HHGW disposal tunnel	UILW vault	RSILW vault	NB SILW vault	SILW vault	LLW vault	DNLEU vault	Shaft & drift	Common service areas
Aluminium (and alloys)	0	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	0	0
Bentonite	26,800	0	0	0	0	0	0	0	0
Cementitious material	157	35,100	31,300	36,000	36,800	8,130	36,500	108,000	11,400
Copper (and alloys)	0	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	0	0
Glass / ceramic Total	0	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	0	0
Halogenated Plastics	0	0.157	0.157	0.157	0.157	0.157	0.157	0	0
Other ferrous metals	38.3	19.3	37.9	37.9	30.4	11.8	11.8	0	0
Other organics	1.35	1.92	1.69	1.69	1.82	1.82	1.82	0	10
Stainless steel	10.1	38.6	38.5	38.5	31.5	31.5	31.5	643	95
Zinc	0	0.168	0.168	0.168	0	0	0	0	0

Table D3 - Estimated material masses associated with GDF construction in an evaporite host rock[47]

	Material mass [t]								
Material	HHGW disposal tunnel	UILW vault	RSILW vault	NB SILW vault	SILW vault	LLW vault	DNLEU vault	Shaft & drift	Common service areas
Aluminium (and alloys)	0	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	$5.25\ 10^{-2}$	0	0
Cementitious material	317	962	962	962	1,060	1,060	1,060	85,800	7,700
Copper (and alloys)	$1.68\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	$4.73\ 10^{-3}$	0	0
Glass / ceramic Total	0	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	$1.55\ 10^{-3}$	0	0
Halogenated Plastics	$2.54\ 10^{-2}$	0.157	0.157	0.157	0.157	0.157	0.157	0	0
Other ferrous metals	38.3	163	163	163	$4.20\ 10^{-3}$	$4.20\ 10^{-3}$	$4.20\ 10^{-3}$	0	0
Other inorganics	0	1,700	929	1,830	3,290	0	2,960	0	0
Other organics	1.96	2.91	2.66	0	0	0	0	0	0
Stainless steel	20.5	36.4	34.7	34.4	36.4	36.4	33.8	101	1,190

Certificate No LRQ 4008580

Radioactive Waste Management Limited
Building 329
Thomson Avenue
Harwell Oxford
Didcot
OX11 0GD

t +44 (0)1925 802820
f +44 (0)1925 802932
w www.nda.gov.uk/rwm