Nuclear Waste Services

2022 Inventory for Geological Disposal

Underpinning Report

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Introduction

The generic Disposal System Safety Case

Nuclear Waste Services (NWS) (formerly Radioactive Waste Management Ltd) is the organisation responsible for delivering a programme for the safe, secure and permanent geological disposal of the UK's most hazardous radioactive waste. Information on the approach of the UK Government and devolved administrations of Wales and Northern Ireland[1] to implementing geological disposal is included in an overview of the generic Disposal System Safety Case (DSSC) [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 engineered 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 although several search areas are being investigated.

To make progress during the siting process, NWS 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 (HSR), for example, granite
- lower strength sedimentary rock (LSSR), for example, clay
- evaporite rock (EVR), for example, halite

The inventory for disposal in the GDF is defined in the UK policy framework for managing radioactive substances and nuclear decommissioning [2]. The inventory includes radioactive wastes and nuclear materials that could, potentially, be classified as wastes in the future. For the purposes of developing disposal concepts, these wastes have been grouped as follows:

- high heat generating wastes (HHGW): that is, spent fuel from existing and future power stations and high level waste (HLW) from spent fuel reprocessing. High fissile activity wastes, that is, plutonium (Pu) and highly enriched uranium (HEU), are also included in this group. These have similar disposal requirements, even though they don't generate significant amounts of heat
- low heat generating wastes (LHGW): that is, intermediate level waste (ILW) arising from the operation and decommissioning of reactors and other nuclear facilities,

[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.

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)

NWS has developed six illustrative geological 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 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 DSSC.

The generic 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. These designs 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 forms a benchmark for NWS to provide waste producers with advice on the packaging of waste for disposal. The suite of documents that make up the generic DSSC, and its high-level structure, are shown in Figure 1.

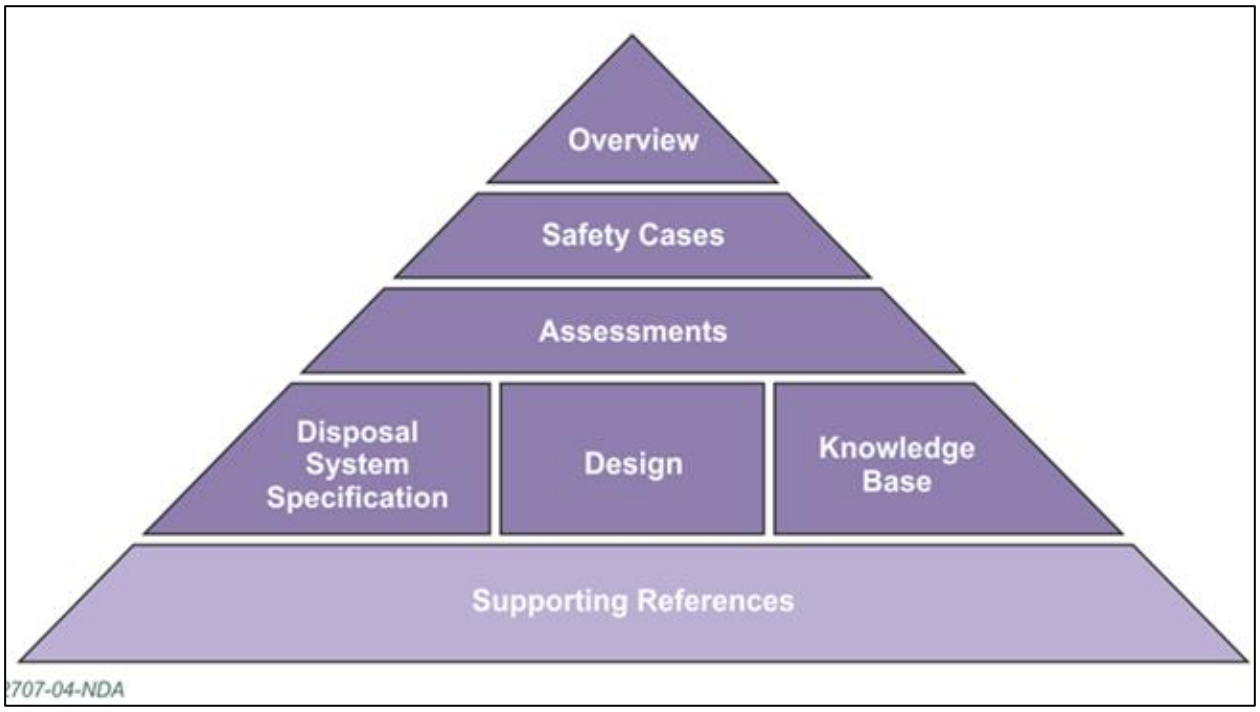

Figure 1 Structure of the generic DSSC.

The 2022 Inventory for Geological Disposal

Objectives of the Inventory for Geological Disposal

The objective of the inventory for geological disposal (IGD) is to provide information on the quantities and characteristics of the components of the inventory of waste destined for geological disposal that is sufficiently detailed for use in NWS' design and safety and environmental assessment work.

The information presented in the inventory includes the volumes, physical and chemical compositions, and activities of conditioned wastes and materials, and details of the containers in which they are assumed to be placed for disposal.

The 2022 IGD scenario was agreed in 2022 and the assumptions that have been made broadly reflect the policies, strategies and intentions at that point in time. However, these are all subject to change and the assumptions in the 2022 IGD may not reflect the current position.

Development of the IGD

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

Currently, the UK Inventory is updated every three years, after which the IGD is updated, as shown in Figure 2. Waste in the UK Inventory dataset that will be managed through other routes (e.g. alternative disposal options and treatment routes) is discounted; the remaining data are reviewed and, where appropriate, enhanced[2]. The dataset is further enhanced to take account of Government policy and industry plans to produce the IGD. Finally, following the production of the UK Inventory (and IGD), Nuclear Decommissioning Authority (NDA) and key users of the UK Inventory (including NWS) meet with waste producers to discuss key inventory improvements. In addition, further characterisation of wastes is carried out, leading to improvements in the inventory data. This iterative process drives continuous improvements in the UK Inventory 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 2022 UK Inventory itself, and with other sources of data; 'Enhancement' is defined as the process of filling gaps and providing justified numeric and other data where these are not reported in the 2022 UK Inventory. For example, the UK Inventory only provides the mass of spent fuels; the enhancement process adds the radionuclide activities and materials and packaging assumptions.

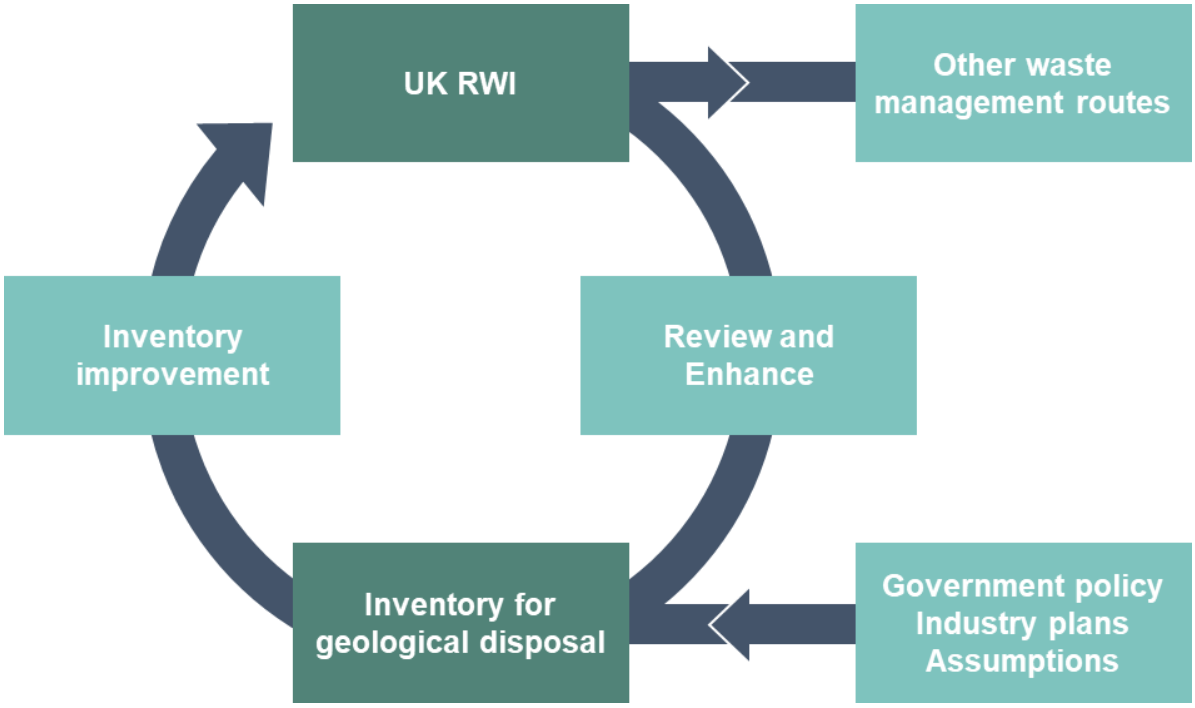

Figure 2 *The iterative development of the inventory for geological disposal.*

The IGD can also be updated in response to inventory data that becomes available between the current three-year cycle of the UK Inventory. Information may become available from several sources, for example from work ongoing within NWS or waste producing organisations.

Scope

Scope of the 2022 Inventory for Geological Disposal

The waste and material types that comprise the IGD are defined in paragraph 8.63 of the UK policy framework for managing radioactive substances and nuclear decommissioning [2]:

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:

- HLW arising from the reprocessed spent nuclear fuel at Sellafield;
- ILW arising from existing nuclear licensed sites, defence, medical, industrial, research and educational facilities that is not suitable for disposal in near surface facilities;
- the small proportion of LLW that is not suitable for disposal in near surface facilities;
- spent fuel from existing commercial reactors (yet to be declared waste) and from research reactors that is not reprocessed;
- spent fuel (yet to be declared waste) from new nuclear projects (including small modular reactors);
- spent fuel (yet to be declared waste) from advanced modular reactors if it is suitable for disposal in a GDF;
- the plutonium inventory (yet to be declared waste) – either as spent fuel following reuse or in an immobilised form suitable for geological disposal;
- uranium stocks – including that arising from enrichment and fuel fabrication activities and reprocessing activities (yet to be declared waste); and
- irradiated fuel and nuclear materials (yet to be declared waste) from the UK defence programme.

Updates to the IGD are typically either

- a full update, which includes a rigorous examination of the entire UK Inventory dataset: the dataset is reviewed and, where appropriate enhanced. Parameters such as those required to support the gas pathway analysis are calculated and the assumptions that underpin the inventory are also reviewed.
- a light update, in which 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 (e.g. calculations of metal geometry to support the gas pathway analysis) are not carried out.

The 2022 IGD is a full update to the IGD.

Scope of this report

This report presents the method for compiling the 2022 IGD including detailed technical information on how the inventory scenario is defined, how inventory data are reviewed and enhanced as part of a full update to the IGD and what assumptions have been made in the process.

This report provides the technical underpinning of the inventory data compiled for the 2022 IGD and reported in the 2022 IGD Main Report [4].

Conventions used

Waste Groups

NWS's generic disposal facility designs [5] recognise the different packaging and disposal processes for different types of radioactive wastes: LLW, ILW and DNLEU are assumed to be disposed of in a LHGW area; HLW, spent fuels (SFs), plutonium and HEU are assumed to be disposed of in a HHGW area. The inventory for geological disposal has been broken down into waste groups (shown in light green boxes 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.

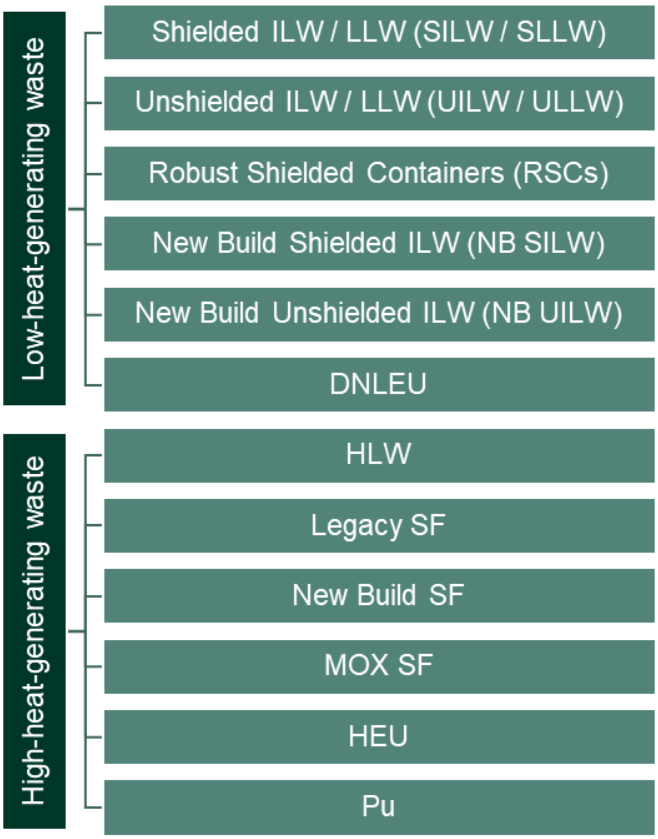

Figure 3 *The two high-level partitions of the inventory (dark boxes) and the waste groups (light boxes).*

Data

The 2022 IGD includes data for:

- volumes: the stored, conditioned, and packaged volume of the inventory
- activities: information for 112 radionuclides identified as being relevant to geological disposal [6]. Data on selected 'priority' radionuclides[3] are presented along with the total activity from all 112 'relevant radionuclides' and their progeny
- the number of disposal units[4] associated with each type of package
- waste material masses: composition data on two levels: (i) the bulk materials that make up the wastes, and (ii) elemental composition of the wastes
- the properties of the inventory that are relevant to the gas pathway analysis.

All data are 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

[3] More detail on priority radionuclides is presented in Appendix A.3

[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.

rounded to three significant figures. This approach ensures an appropriate and consistent level of precision in all the data.

The 2022 IGD reporting structure

The 2022 IGD reports

This document is the '2022 IGD Underpinning report' and is one of five reports that deal with the various aspects of the 2022 IGD; the full suite of reports comprises:

- The 'Main Report' [4], which describes the key features of the IGD to a technical audience
- The 'Underpinning Report', which describes how IGDs are developed and updated
- The 'Implications Report' [7], which describes the implications of the changes introduced by the 2022 IGD for the generic DSSC
- The 'Key Changes Report' [8], which sets out the differences between the 2022 IGD and the previous iteration (the 2019 IGD)
- The 'Summary' [9], which describes the key features of the report to a non-technical audience

Report structure

The remainder of this report is structured as follows:

- *Scenario for the Inventory for Geological Disposal* defines the reference and alternative inventory scenarios
- *Review and Enhancement of Data* details the review and enhancement processes involved in updating the IGD
- *Summary* provides a short summary of the above

In addition, there are four appendices:

- *Appendix A: Data enhancement and characterisation provides details of the method for the review and enhancement of wastes in the IGD, including any assumptions made*
- *Appendix B: Waste containers provides details of the waste containers in the 2022 IGD*
- *Appendix C: Conditioning and capping materials provides the methodology for assigning the conditioning and capping materials and their material compositions*
- *Appendix D: Construction and operating materials provides an estimate of construction and operation materials that will remain underground after closure*

Scenario for the Inventory for Geological Disposal

In the context of the IGD, a 'scenario' is the description of how the waste and nuclear materials will arise and be managed. The IGD scenarios are defined by considering the policies, strategies and plans which impact them.

The specific types of higher activity wastes (and nuclear materials that could be classified as waste) which would comprise the IGD are defined in the UK policy framework for managing radioactive substances and nuclear decommissioning [2]. The IGD reference scenario is NWS's best estimate of how these wastes will arise. To investigate uncertainties in the IGD, two alternative scenarios have also been developed, see *Description of alternative scenarios*.

Policies, strategies and plans which influence scenarios

Waste management strategies and policies

The policies for management of radioactive substances and nuclear decommissioning in the UK have been consolidated into a single UK policy framework [2]. The policies of the UK Government and Northern Ireland Executive as well as the Welsh Government are that the most hazardous radioactive wastes in England and Wales should be managed 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 higher activity radioactive wastes arising in Scotland to be managed in near surface facilities[5] [10]. Waste that is covered by the Scottish Government's policy[6] is, therefore, excluded from the IGD.

The data for future waste arisings in the UK Inventory 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 2022 UK Inventory, these projections represent planning assumptions at 1 April 2022. The UK Inventory 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.

A scenario is used to describe how the waste and material types arise. The IGD reference scenario is NWS's best estimate of how the waste will arise; alternative scenarios have also been considered to assess uncertainties.

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[5] 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 [10].

[6] The policy does not cover radioactive waste 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 polices of previous governments.

Existing reactor operation

The operation of existing reactors in the UK could influence the amount and properties of waste destined for geological disposal. All Advanced Gas-cooled Reactors (AGRs) are set to cease generating electricity by 2028. However the cumulative years of station operation (as of 2022) is 272 years with only a further 16 years cumulatively forecast; any changes made to the end dates of remaining AGR operations would therefore be small in comparison to the overall operational period of the fleet.

Sizewell B is currently assumed to operate for 40 years, but it is possible that this could be extended; indeed, EDF have recently announced that they are looking to extend the lifetime of the reactor by at least 20 years [11].

Management of plutonium

At the time the 2022 IGD was developed, 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 [12]. Since the development of the IGD scenarios, the UK Government has taken the policy decision to immobilise the UK's inventory of civil separated plutonium at Sellafield [13].

For the 2022 IGD the assumptions regarding MOX have been decoupled from those for a new build programme. Therefore, 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 fraction in the MOX fuel has been included.

New build

The term "new build" is used to cover reactors that are not yet operational (the reactors currently being built at Hinkley Point C are therefore considered to be new build reactors). The inventory will be sensitive to the size, composition and timing of a new build programme: the size will determine the total quantity of waste; the composition will determine the materials used; and the timing will have implications for the activity of the waste produced.

At the time the IGD was developed, policy published under the previous government set out increased ambitions for deployment of civil nuclear power up to 24 GW(e) by 2050, which could include both large scale and small modular reactor technologies.

Uranium

The quantity of uranium that needs to be disposed of will depend upon how long enrichment activities continue in the UK. Enrichment of uranium is a commercial activity and the fuel for any new build reactors will not necessarily come from a UK enrichment plant. Commercial factors may mean that fresh uranium is not used as the feedstock for new enrichment activities.

Ministry Of Defence materials

The Ministry of Defence's (MOD's) uranium, plutonium and irradiated submarine fuel are not reported in the UK Inventory; however, some information is available in the nuclear liabilities management strategy [14], which identifies the GDF as a possible endpoint for all these materials.

The quantity of waste and irradiated submarine fuel generated from the submarine decommissioning programme will depend upon the number of submarines that need to be decommissioned.

Description of reference scenario

Existing facilities

The data for future waste arisings in the UK Inventory are projections made by the organisations that operate the sites where radioactive waste is generated. *Figure 4* is based on the scenario for the 2022 IGD and provides a high-level overview of the timings for the different activities; full details are provided in Table A-1, while Table A-2 provides details of the scenario broken down by waste group.

The operational periods are current estimates and are likely to change when safety cases are renewed; decommissioning plans are still being formulated in many instances. A 40-year operational period has been assumed for Sizewell B in developing the 2022 IGD.

Changes to the operational lifetimes of existing reactors have not been considered in the 2022 IGD scenarios because:

- no significant changes are expected to the AGR operational lifetimes, and any changes would only result in a small additional amount of AGR operational wastes
- the quantity of waste from an additional 20 years of operations at Sizewell B will be small (and similar in characteristics) when compared to the wastes arising from an assumed new build programme.

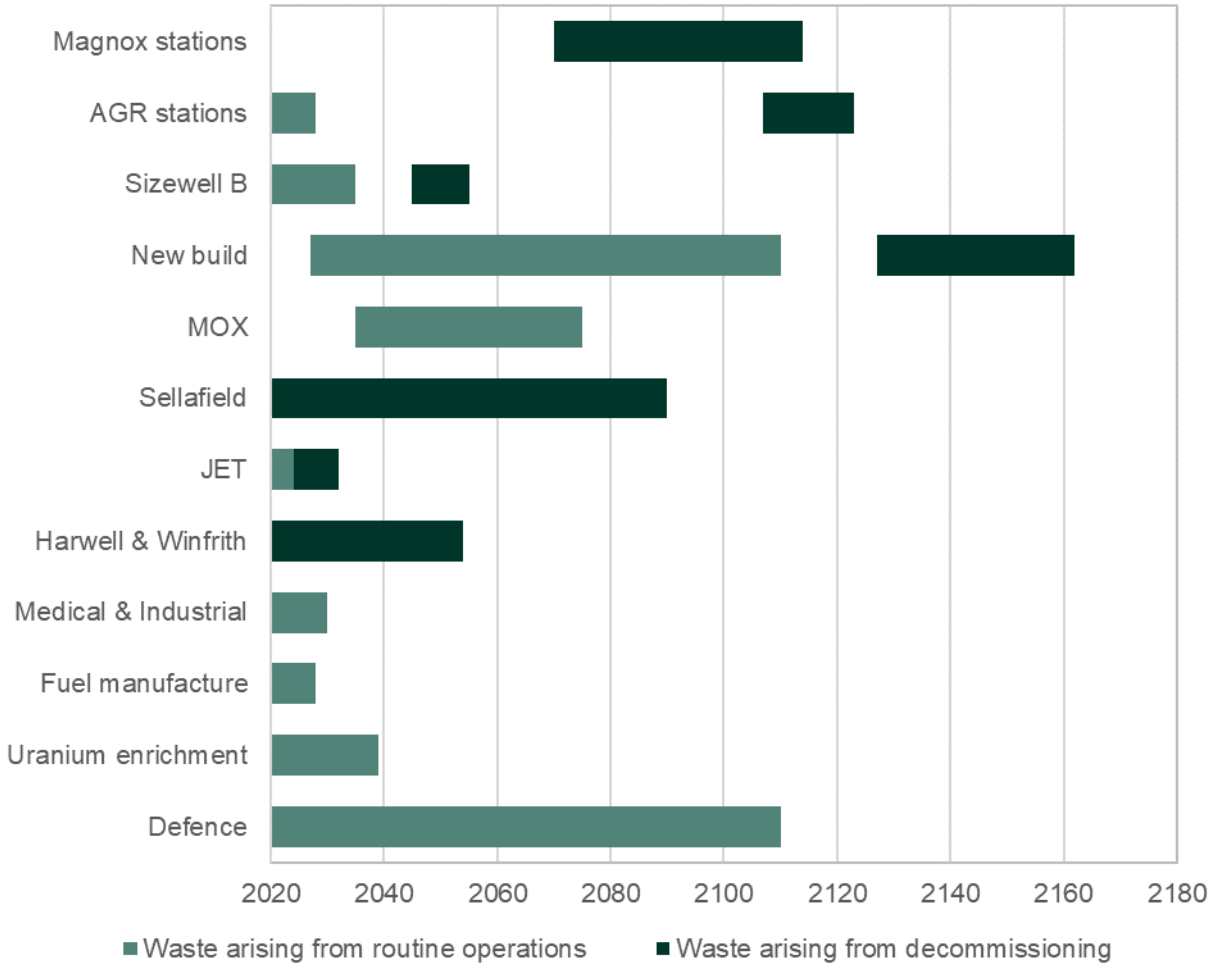

Figure 4 *Figure showing periods of waste arising from operations and decommissioning.*

Assumptions

The reference scenario presents an inventory that adopts the assumptions for waste from legacy facilities as given in the previous section and considers the factors detailed in each of the following sub-sections.

Legacy spent fuels

For legacy SF the reported masses are taken from the latest published UK Inventory and split into streams based on the origin and characteristics of the material.

Management of plutonium

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 are uncertain; and
- government policy allows the UK to take title to overseas plutonium under commercial terms (see paragraph 1.8 of [12]]) 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 could be converted to MOX. The remaining 5% is assumed to be disposed of using the can-in-canister concept[7] as PuO_2. Since the development of the IGD scenarios, the UK Government has taken the policy decision to immobilise the UK's inventory of civil separated plutonium at Sellafielld [13].

New build

The 2022 IGD reference dataset includes a new build programme of 24 GW(e)[8], assumed to comprise of Hinkley Point C (currently under construction), Sizewell C and a fleet of SMRs / AMRs. The operational and decommissioning periods in this scenario are:

- Hinkley Point C[9] (capable of generating 3,260 MW(e)) operating from 2027 to 2087.
- Sizewell C (capable of generating 3,260 MW(e)) operating from 2035 to 2095.
- The remaining 18 GW(e) of nuclear generation capacity by 2050 is assumed to be made up of SMRs / AMRs, based upon 1 GW(e) becoming operational every year from 2033 to 2050 and operating for 60 years.
- Decommissioning after a 40-year cooling period.

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[7] 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.

[8] Whilst Government position regarding the extent and pace of new build is developing, this assumption is broadly consistent with the UK policy framework for managing radioactive substances and nuclear decommissioning published under the previous government.

[9] The operational date for Hinkley Point C was taken from the 2022 Inventory at which time it was scheduled to become operational in June 2027. A more recent press release from EDF states this date has been re-evaluated and the new target year of operation is 2029 [31].

Uranium

The current assumption is that the uranium oxide form destined for geological disposal will be UO_2 for Highly Enriched Uranium (HEU), and UO_3 or U_3O_8 for Depleted, Natural, and Low Enriched Uranium (DNLEU).

Were the uranium for new build reactor fuel to be enriched in the UK, it could result in a significant addition to the DNLEU inventory which is considered in the alterative scenarios (see Description of alternative scenarios).

Defence materials

For the purposes of developing the IGD, NWS have included MOD materials based on three main assumptions:

- Only materials that are within international safeguards at the time of disposal are included[10]
- MOD materials will be managed in the same way as the equivalent civil materials
- Quantities are as reported in the 2022 Nuclear Liabilities Management Strategy [14]

Irradiated submarine fuel

Since the 1960s the Royal Navy has operated nuclear powered submarines that contain pressurised water reactors. The irradiated submarine fuel has no direct comparisons in the inventory for geological disposal: the legacy civil fuels have lower enrichment and are clad in different materials.

It is assumed that fuel from all three iterations of the Royal Navy's pressurised water reactor design[11] will be disposed of via the GDF. The MOD will conduct a number of disposability assessments for irradiated fuel working with NWS as the concept for GDF disposal of civil spent fuel matures. The output of these assessments will allow MOD to agree a packaging and conditioning arrangement for irradiated fuel that will meet the acceptance criteria for a GDF.

Additionally, MOD has two types of research reactor fuel; these are small in comparison to the quantities of other fuels in the IGD and have not been quantified.

To deliver best value for money for the UK taxpayer, MOD will collaborate with the NDA at the appropriate time in the future to use UK civil legacy spent fuel conditioning and packaging infrastructure for their irradiated fuel.

The mass of irradiated submarine fuel in the IGD will be significantly smaller than the contributions from legacy civil reactors.

Uranium

MOD uranium liabilities were approximately 15% (by mass) of the total NDA uranium liabilities [14]. Based on the 61,000 tU (tonnes of uranium) reported by NDA [15], MOD stocks have been assumed to be approximately 9,000 tU.

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[10] MOD anticipate placing the irradiated fuel into international safeguards at the point of disposal [14]

[11] The Royal Navy has liabilities from the Pressurised Water Reactor (PWR) 1 & 2 designs currently with PWR 3 coming into service in the early 2030s.

The largest component of the MOD's uranium liabilities is in the form of uranium hexafluoride; the MOD also holds smaller quantities of uranium oxide and metal. For the purposes of developing the 2022 IGD, NWS has assumed that:

- 5,000 tU of the material is in the form of UF_6 that has been transferred to NDA and was reported in the UK Inventory.
- The remaining 4,000 tU is Magnox depleted uranium (MDU) that is managed in the same way as the civil MDU.

Plutonium

The UK is currently a nuclear weapons state and strategic materials are not destined for the GDF. However, if this were to change then it is expected that the options for the military stocks of plutonium would be considered in the same way as the UK's civil stocks of plutonium have been considered. The MOD has already placed plutonium that is surplus to requirements into International Safeguards; this material will be treated in the same way as civil material.

It is expected that all of the MOD's plutonium would be suitable for use as MOX fuel and that the quantity is small when compared with the anticipated stock of civil plutonium. For the purposes of developing the 2022 IGD, the MOD's stocks of plutonium are assumed to be 2 t of plutonium [14] and this is assumed to be managed in the same way as the civil plutonium so that the GDF has sufficient capacity for this eventuality.

Packaging assumptions

Data for legacy wastes are taken from the latest UK Inventory and enhanced where IGD data requirements are not met. For packaging, conditioning and capping materials the requirement is that for each waste stream in the IGD, the waste is packaged in a single package type of standard NWS design. The waste is also expected to be conditioned and capped where appropriate, depending on the wasteform. The data are reviewed and enhanced as described in a later section (see *Review and Enhancement of Data*).

Description of alternative scenarios

To explore the impact on the IGD of changes in assumptions and uncertainties in data, NWS has defined two alternative scenarios. These scenarios are chosen so as to identify the changes to the waste quantities, waste characteristics or assumptions that have the greatest potential to affect NWS's designs and safety cases. The current alternative scenarios cover:

- a larger alternative scenario (B) – designed to show a larger total inventory of radioactive waste and materials for geological disposal.
- a smaller alternative scenario (C) – designed to show a lower total inventory of radioactive waste and materials for geological disposal.

Along with the size of the overall inventory, how much of the inventory is routed to a GDF for disposal is also considered.

Scenario B

The scenario uses the same assumptions as for the reference inventory with the addition of depleted uranium tails arising from the enrichment of reactor fuel for 24 GW(e) of new build reactors included in the inventory.

The mass of DU tails can be calculated using

$$m_{U(tails)} = m_{U(fuel)} \times \frac{U235\%_{(fuel)} - U235\%_{(natural)}}{U235\%_{(natural)} - U235\%_{(tails)}}$$

The mass of DU tails associated with a single UK EPR reactor was calculated using a mass of 527.5 kgU per assembly [16], giving 1376.8 tU of fuel over the reactor's lifetime. The other parameters used in the calculation are recorded in Table 1[12].

This results in a total mass of DU tails associated with a 1.6 GW(e) UK EPR of 14,030 tU, which has been divided by 1.6 (to get a tonnage per GW(e)) and multiplied by 24 to give a total of 210,000 tU of DU tails associated with 24 GW(e) of new build.

The additional depleted uranium is assumed to be the same as the depleted uranium currently generated from enrichment activities. As such, it is assumed that it will be managed in the same way (U_3O_8 powder in DV-70s, with four DV-70s in a 2.3 m high transport and disposal container.

Table 1 Parameters used for calculation of additional DU tails

Uranium	U235	U238	Comment
New build fuel	5%	95%	Consistent with GDA disposability assessment [16]
Uranium tails	0.3%	99.7%	Consistent with legacy DU tails assumption
Natural uranium	0.72%	99.28%	

Scenario C

The scenario uses similar assumptions to the reference scenario with a key difference being a new build programme of only 16 GW(e) is assumed. The programme is assumed to comprise Hinkley Point C, Sizewell C and a fleet of Small Modular Reactors (SMRs) / Advanced Modular Reactors (AMRs). Reactors are assumed to become operational in 2027 (Hinkley C), 2035 (Sizewell C) and then 1 GW(e) every two years from 2034 – 2050.

Wastes that have the potential to be suitable for thermal treatment are assumed to be thermally treated and routed to a GDF.

Additionally, it is assumed that the following wastes will not be disposed of in the GDF:

- Wastes that are potentially suitable for near-surface disposal are assumed to go to a near-surface disposal facility
- DNLEU, which is assumed to be held in abeyance

[12] Enrichment of uranium is a commercial activity and the fuel for any new build reactors will not necessarily come from a UK enrichment plant. Commercial factors may mean that fresh uranium is not used as the feedstock for new enrichment activities.

Review and Enhancement of Data

The UK Inventory does not contain information on the quantities and characteristics of the components of the inventory in sufficient detail for use in NWS's GDF design, safety and environmental assessment work. Consequently, the production of the IGD involves reviewing and enhancing the UK Inventory for legacy waste and other publicly available data for the other wastes, spent fuels and nuclear materials.

For the purposes of this work:

- 'Review' is defined as the process of identifying omissions, differences and inconsistencies within the UK Inventory itself, and with other sources of data
- 'Enhancement' is defined as the process of filling gaps, amending anomalies and providing fully justified numeric and other data where these are not reported in the UK Inventory

Potential improvements identified in UK Inventory data through the review and enhancement process are prioritised and fed back into the next UK Inventory.

The review and enhancement method is different for 'full' and 'light' updates to the IGD. 'Full' updates include a rigorous examination of the entire UK Inventory dataset and a challenge of assumptions, whereas a 'light' update carries over many of the assumptions from the previous 'full' update. The process for developing a 'light' update and a full update are described in the following sub-sections.

When determining whether a full update or a light update is appropriate, NWS will consider a range of factors, including whether a significant change in the underpinning assumptions is required, and whether there is a requirement for re-baselining from other work.

Review and enhancements for a light update

Before beginning the process of enhancing, the packaging rules from the previous inventory are reviewed and, if appropriate, updated. Details of the packaging rules for the 2022 IGD can be found in Packaging, conditioning and capping.

For a 'light' update of the IGD the substantial enhancements carried out for a full update are carried across where appropriate rather than repeating the work. The enhancement process for a 'light' update is described below:

- For legacy waste streams that are included in the IGD scenario, the enhancement process is illustrated in Figure 5. Where possible, enhancements from the previous inventory are carried forward; a waste stream will always be enhanced to ensure that it has a package type that has completed NWS's change management process.
- For nuclear materials and spent fuel, enhancements are carried over from the previous IGD without change (other than to reflect the change in the quantities and scenario).
- For a new build programme defined in the scenario for inclusion in the IGD, data are taken from publicly available sources for new reactors and enhanced where data are missing.

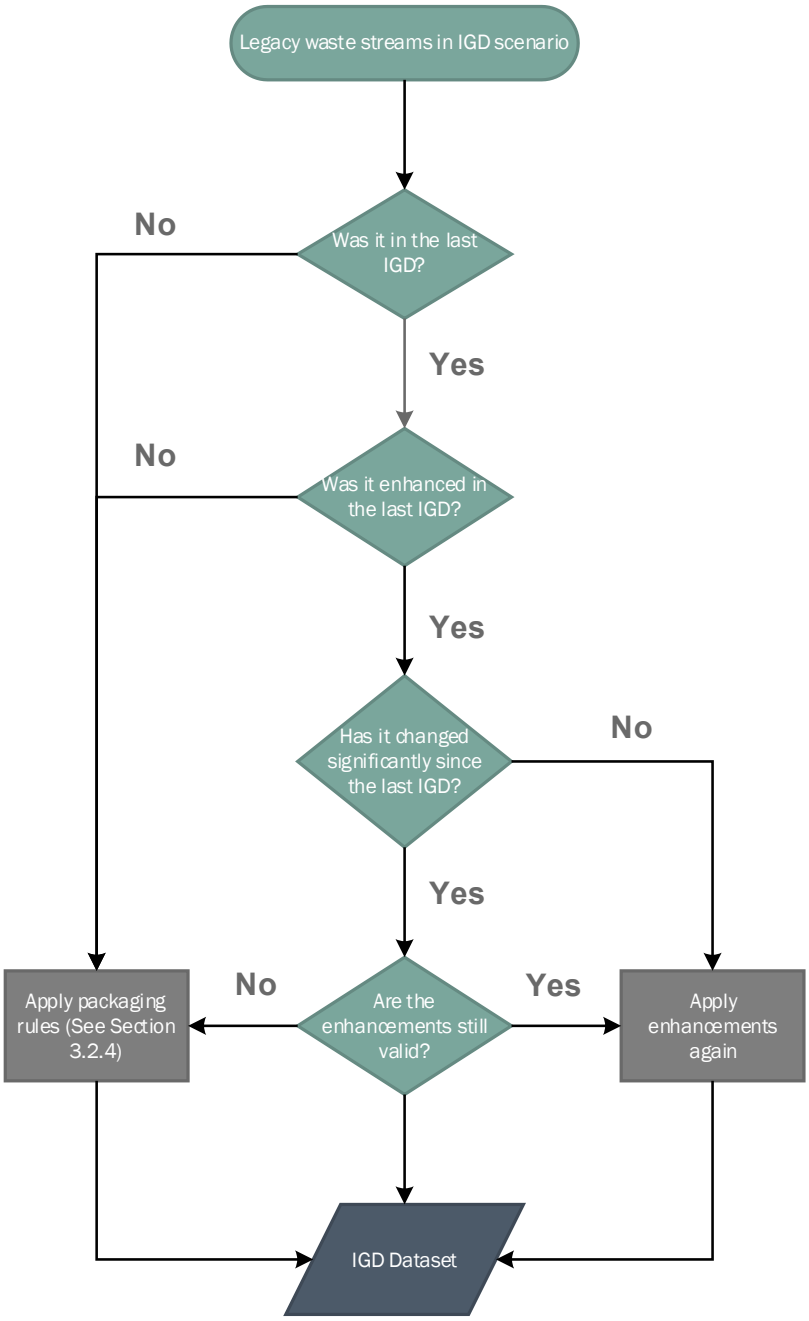

Figure 5 *The process for enhancing legacy streams in the IGD.*

Review and enhancements for a full update

The following sub-sections provide a summary of the review and enhancement process for a full update; the full details are reported in:

- *Appendix A: Data enhancement and characterisation*
- *Appendix B: Waste containers*
- *Appendix C: Conditioning and capping materials*
- *Appendix D: Construction and operating materials*

Waste volumes and quantities of nuclear materials and spent fuel

The method for deriving quantities of waste and nuclear materials for the IGD depends on the origin of the waste and its waste group. For waste streams that are defined in the scenario for inclusion in the IGD, the process is described below for each waste group shown in Figure 3

- For the SILW / SLLW, UILW / ULLW and RSC waste groups, the stored volumes from the latest published UK Inventory are used.
- For High Level Waste (HLW), the UK Inventory reports the 'packaged' volume of waste to be the vitrified glass and stainless steel waste vitrification plant (WVP) canister. This is defined as the 'stored' volume in the IGD as the WVP canisters are then assumed to be packaged into mild steel disposal containers for emplacement in a GDF.
- For legacy spent fuels and nuclear materials (DNLEU, HEU, plutonium), the reported masses from the latest published UK Inventory are used and split into streams based on the origin and characteristics of the material. For quantities not reported in the UK Inventory (e.g. nuclear materials from defence operations), the latest publicly available data are reviewed for inclusion in the IGD and the quantities are agreed for use with the material owner.
- For new build waste and SF (new build SILW, new build UILW, new build SF), relevant published documentation (e.g. GDA disposability assessments) are reviewed for waste quantities per reactor; information for operational waste from Hinkley Point C published in the latest UK Inventory is also reviewed.
- For MOX SF, the quantities of plutonium suitable for re-use in MOX fuel are taken from NDA and MOD documents, and then discussed with NDA and MOD before use in the IGD.

Waste materials composition

Data for legacy wastes are taken from the latest UK Inventory and enhanced where data requirements are not met. Data for new build wastes are taken from the GDA or best publicly available documents, and enhanced where data requirements are not met.

The review and enhancement of the material composition of waste streams largely comprises identifying inconsistencies and omissions within the UK Inventory. An example is checking that the aqueous liquid component of an ion exchange resin or sludge stream has not been double counted with the interstitial liquid of the waste.

Assumptions are also made to improve the characterisation of waste streams for certain overarching material types that comprise several different components. An example of this is where a quantity of halogenated plastic is given for a waste stream, but the type of halogenated plastic is not specified. In such a case an assumption is made, e.g. that the plastic is polyvinyl chloride (PVC).

The full detailed methodology for the review and enhancement process is reported in Appendix A.4 for legacy wastes and Appendix A.7 for new build waste.

Nuclear material and SF composition

The UK Inventory reports only tonnes of heavy metal (tHM) quantities of aggregated legacy nuclear materials and SF. Material compositions therefore need to be sourced. Full details of the enhancement process are provided in the appendices and a summary is included below.

- For legacy SF (see Appendix A.5), the material composition includes the fuel, cladding and other fuel assembly components that will be disposed of in a GDF. The material compositions have been developed following discussions with the material owners.
- Uranium and Plutonium (see Appendix A.6) are classed as 'heavy metal oxide', with the current assumption that the oxide form destined for geological disposal will be UO_2 for HEU, UO_3 and U_3O_8 for DNLEU and PuO_2 for plutonium. The material composition for each of these wastes is
    - the heavy metal content plus impurities (e.g. nitrates, sulphates), where the information is available

- internal waste packaging materials of the overall disposal container. These are also included in the waste composition for streams with more developed packaging assumptions (currently DNLEU Transport and Disposal Containers (TDCs))

- For new build SF (see Appendix A.7.2) the data are taken from GDA disposability assessments or the best publicly available documents. The material composition of SF comprises the uranium oxide fuel, cladding and other fuel assembly components together for disposal.
- For MOX SF (Appendix A.8), in absence of new information the assumptions agreed with NDA for previous iterations of the IGD have been carried over. These include assumptions about its composition, use in MOX fuel fabrication and utilisation of the fuel in reactors. The MOX SF material composition comprises the fuel, cladding and other fuel assembly components together for disposal.

Packaging, conditioning and capping

Data for legacy wastes are taken from the latest UK Inventory and enhanced where data requirements are not met. For packaging, conditioning and capping materials, the requirement is that, for each waste stream in the IGD, the waste is packaged in a single package type of standard NWS design. The waste is also expected to be conditioned and capped where appropriate, depending on the wasteform. Where this information has not been submitted in the UK Inventory the data are reviewed and enhanced as described below.

There cases where the waste packaging is reviewed are:

1. Waste streams where the container type has not been specified

Where the waste producer has not specified the waste container type in the 2022 UK Inventory, the following assumptions have been made. First, where relevant, the way in which other waste streams are packaged on the site have been considered. If there is no obvious package allocation, then waste packages stored onsite have been considered as the most likely to be used. If there is still no obvious package allocation, the following logic has been followed:

- For operational ILW streams

  If the waste is compactable (e.g. Plutonium Contaminated Material (PCM)) then the enhanced 500 litre drum (with pre-cast annulus) has been assumed.

  If the waste comprises larger components unsuitable for 500 litre drums, then

  if the waste stream is at Sellafield, the Sellafield $3m^3$ box has been assumed,

  if the waste is not at Sellafield, $3m^3$ boxes (side lifting) have been assumed.

otherwise

  Standard 500 litre drums have been assumed.

- For decommissioning ILW streams

  The package assumed is based on comparisons made with

  similar waste streams if any exist, otherwise

  with other waste streams from the same site.

  If no comparators are available, 4m boxes have been assumed, with verification that the package dose rate and heat output do not exceed the transport limits

  If the transport limits are exceeded, then

  if the waste is at Sellafield, the Sellafield $3m^3$ box has been assumed,

  if the waste is not at Sellafield, $3m^3$ boxes (side lifting) have been assumed.

2. Waste streams where a non-standard container is specified

For ILW and LLW, the IGD uses only waste containers that have completed NWS's change management process and have a detailed waste package specification.

The following non-standard containers have been reallocated:

- Wastes in 500 l Robust Shielded (RS) drums containing lead shielding have been reassigned with a 1:1 mapping to 500 l RS drums without any added lead shielding.
- Sellafield wastes assigned to 3 m^3 decommissioning concrete containers have been reassigned to 3 m^3 enhanced Sellafield boxes.

For all other non-standard containers reported:

- If the non-standard container is specified to be overpacked into an NWS standard container, that allocation has been adopted, otherwise
- A standard NWS disposal container has been assigned after considering the packaging
  - of similar waste streams if any exist, otherwise
  - of waste streams from the same site

Missing conditioning and capping data fields were enhanced following the methodology in *Appendix C: Conditioning and capping materials*.

Data for new build ILW are taken from the operational waste streams in the 2022 UK Inventory for the Hinkley Point C reactors under construction and GDA documents; details of the enhancements are reported in Appendix A.7.

No packaging data are reported in the UK Inventory for SF or nuclear materials. Illustrative package designs have been developed by NWS. Details of the waste packages and assumptions that have been made are reported in *Appendix B: Waste containers.*

Radioactivity

Data for legacy wastes are taken from the latest UK Inventory; radioactivities are reviewed for anomalies and, where appropriate, enhancements are made following the methodology reported in Appendix A.4.4. The UK Inventory currently does not include radioactivity data for nuclear materials or SF. NWS has calculated radionuclide inventories for each nuclear material and SF stream based on publicly available data on materials (including impurities) and irradiation conditions (for SF). NWS has made high level assumptions regarding the irradiation of each waste stream. The assumptions and method for deriving the radionuclide inventories are reported for each waste group in *Appendix A: Data enhancement and characterisation*.

New build decommissioning ILW and SF radionuclide inventories have been taken from the GDA disposability assessment reports, and for operational ILW streams from the 2022 UK Inventory.

Elemental composition

Material grades and types are assigned to all bulk materials and elemental compositions / specifications for these bulk materials are then used with the material masses to derive elemental masses. The approach is detailed below:

1. Allocate material grades to steels, other metals and alloys and to proprietary material types such as exchange resins.
2. Where the total mass of a material component in a waste stream is made up of a number of different grades (e.g. stainless steel), assign proportions to each grade.

3. Where specific material grades or types are not reported, NWS have assigned them in the same relative proportions as the major contributing streams where grades are reported.

4. Once material grades have been established for all of the components, the elemental masses are determined using the database of elemental compositions. The process can be expressed mathematically as follows:

   The elemental composition (from hydrogen to californium) of each waste group is calculated by the equation below:

$$\begin{pmatrix} \mathbf{H} \\ \vdots \\ \mathbf{Cf} \end{pmatrix} = \sum_{\boldsymbol{n}} \sum_{\boldsymbol{i}} \left(\mathbf{m}_{\boldsymbol{i}} \times \begin{pmatrix} \mathbf{H}_{\boldsymbol{i}} \\ \vdots \\ \mathbf{Cf}_{\boldsymbol{i}} \end{pmatrix} \right)_{\boldsymbol{n}}$$

   Where n is each bulk material type in the waste group (such as stainless steel), i is each grade of that bulk material type (such as stainless steel 306), m_i is the total mass of grade i, $\begin{pmatrix} \mathbf{H}_{\boldsymbol{i}} \\ \vdots \\ \mathbf{Cf}_{\boldsymbol{i}} \end{pmatrix}$ is the composition of grade i and $\begin{pmatrix} \mathbf{H} \\ \vdots \\ \mathbf{Cf} \end{pmatrix}$ is the total mass of each element in the waste group.

The methodology for assigning grades to the bulk materials is reported separately for each waste in the appendices.

Gas generation data

Many radioactive wastes contain materials that produce gas when they corrode, degrade or interact with radiation. NWS's current understanding of gas generation and migration processes during periods before and after closure of the GDF is summarised in reference [17]). Gas is generated by corrosion of metals, degradation of organic wastes (particularly cellulose) and by radiolysis. The most important gases volumetrically are hydrogen, carbon dioxide and methane. A small proportion of the generated gas can be radioactive, containing H-3 and C-14. In order for NWS to carry out performance assessment calculations, mass and geometry information are required for reactive metals (such as Magnox, aluminium and uranium) and less reactive metals (such as stainless and mild steels and Zircaloy). This is done by representing the metals in waste streams as plates or spheres and assigning a thickness or radius. In addition, the H-3 and C-14 activity associated with the gas-generating materials are determined.

Appendix A.9 shows the methodology implemented in the 2022 IGD.

Summary

The 2022 IGD represents a full update to the IGD which has been developed following an update to the UK Inventory. This has involved a rigorous interrogation of the entire UK Inventory dataset and a review of underpinning assumptions. To describe how waste and nuclear materials are expected to arise in the IGD and explore plausible alternatives, a set of scenarios have been developed. This report details the technical underpinning for these, summarised below.

The reference scenario for the 2022 IGD represents a reference inventory which is consistent with strategies and plans and policies in place on the inventory stock date[13]. The wastes described in the reference scenario are based on current available technologies and how the waste is currently expected to be routed. Alternative scenarios have been developed to underpin credibly larger and smaller inventories. The three scenarios are:

- Reference scenario: based on current policy ambitions, strategies and plans (see Assumptions) which includes an assumed new build programme of 24 GW(e) by 2050.
- Scenario B: which includes additional depleted uranium tails arising from the enrichment of reactor fuel for the 24 GW(e) new build programme, resulting in a credibly larger inventory.
- Scenario C: which assumes a smaller new build programme of 16 GW(e) by 2050 and assumes DNLEU is held in abeyance and does not come to a GDF. Additionally, wastes potentially suitable for thermal treatment are assumed to be treated, and wastes potentially suitable for near-surface disposal are assumed to be routed to a near-surface disposal facility, resulting in a credibly smaller inventory.

The IGD has been developed based on the information and assumptions provided in the UK Inventory, and with a full review and enhancement of the data. For each waste stream in the IGD, this included activities such as:

- Reviewing the waste package assignments
- Reviewing material components of each waste stream
- Applying material grades to bulk materials to enable derivation of elemental masses
- Reviewing radionuclide activities and filling gaps
- Deriving inventories not included in the UK Inventory (e.g. new build, spent fuel[14])

Full details of the review and enhancement approach applied, and any assumptions made, are provided in the appendices.

[13] These are all subject to change and the assumptions in the 2022 IGD may not reflect the current position

[14] For legacy spent fuel, only the masses are provided in the UK Inventory.

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Glossary

Term	Definition
AGR	Advanced Gas-cooled Reactor
AMR	Advanced Modular Reactor
ANDRA	The French National Radioactive Waste Management Agency
AP1000	The Westinghouse Advanced Pressurised Water Reactor design
BFS	Blast Furnace Slag
Conditioned volume	Volume of the wasteform (waste plus immobilising medium) within the container
Cooling time	Also known as decay period, measured from the end of irradiation
DF	Decontamination Factor
Disposal unit	A waste package, or group of waste packages, which is handled as a single unit for the purposes of transport and/or 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
EDF	EDF Energy, the British subsidiary of French state owned Électricité de France
EPR	EPR is now used by AREVA as a reactor name. It was previously used to mean European Pressurized Reactor and Evolutionary Power Reactor.
EVR	Evaporite Rock
GDA	Generic Design Assessment
GDF	Geological Disposal Facility
GW(e)	Gigawatts electrical
GWd/tHM	Gigawatt days per tonne of heavy metal (1 tonne = 1,000 kg)
GWd/tU	Gigawatt days per tonne of uranium (1 tonne = 1,000 kg)
HAW	Higher Activity Waste
HDPE	High Density Polyethylene
HEU	Highly Enriched Uranium
HHGW	High Heat Generating Waste
HLW	High Level Waste
HSR	Higher Strength Rock
IAEA	International Atomic Energy Agency
IGD	Inventory for Geological Disposal
ILW	Intermediate Level Waste
ISO	International Organisation for Standardization
JET	Joint European Torus
LEU	Low Enriched Uranium

Term	Definition
Legacy waste	Radioactive waste which already exists or whose arising is committed in future by the operation of an existing facility
LDPE	Low Density Polyethylene
LHGW	Low Heat Generating Waste. Some wastes have negligible heat output; these are included in this category
LLW	Low Level Waste
LLWR	The Low Level Waste Repository
LSSR	Lower Strength Sedimentary Rock
LWR	Light Water Reactor
MBGWS	Miscellaneous Beta Gamma Waste Store
MDU	Magnox Depleted Uranium
MOD	Ministry of Defence
MOX	Mixed Oxide Fuel
MSSS	Magnox Swarf Storage Silo
NAPLs	Non-Aqueous Phase Liquids
NB	New build
NDA	Nuclear Decommissioning Authority
NWS	Nuclear Waste Services
OPC	Ordinary Portland Cement
Packaged volume	Volume occupied by waste package when waste has been packaged
Payload	Volume of waste (when conditioned) in each waste container
PCM	Plutonium Contaminated Material
PCSR	Pre-Construction Safety Report
PFA	Pulverised Fuel Ash
PFR	Prototype Fast Reactor
ppm	Parts per million
Pu	Plutonium
PVC	Polyvinyl Chloride
PWR	Pressurised Water Reactor
RS	Robust Shielded
RSC	Robust Shielded Container
SF	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	Stream Generating Heavy Water Reactor
SILW	Shielded ILW
SKB	The Swedish Nuclear Fuel and Waste Management Company
SLLW	Shielded LLW
SMR	Small Modular Reactor
SS	Stainless Steel

Term	Definition
SWTC	Standard Waste Transport Container
TDC	Transport and Disposal Container
tHM	Tonnes of heavy metal (1 tonne = 1,000 kg)
THORP	Thermal Oxide Reprocessing Plant
TMF	Tails Management Facility
TPU	THORP product uranium
tPu	Tonnes of plutonium
tU	Tonnes of uranium (1 tonne = 1,000 kg)
U	Uranium
UILW	Unshielded ILW
UK Inventory	The UK Radioactive Waste and Materials Inventory, can also be referred to as the UK RWI or UK RWMI
ULLW	Unshielded LLW
WAGR	Windscale Advanced Gas-cooled Reactor
WVP	Waste Vitrification Plant

Appendix A: Data enhancement and characterisation

A.1 Timings and durations of activities

Table A-1. The timings and duration of activities in the 2022 IGD scenario.

Sector	Assumptions[15]
Civil nuclear power stations	Sizewell B shuts down in 2035 AGRs: Shuts down in 2022: Hinkley Point B, Hunterston B Shuts down in 2024[16]: Heysham 1, Hartlepool Shuts down in 2028: Heysham 2, Torness Deferral of Magnox and AGR final stage decommissioning for up to about 85 years after shutdown; all decommissioning complete by 2123 Prompt decommissioning of Sizewell B (completed by 2053) New build programme of 24 GW(e) comprising twin EPR stations at Hinkley Point C and Sizewell C along with a balance of 'per GW' reactors. 60 years operation each; deferral of decommissioning until 40 years after reactor shutdown
Plutonium	In discussions with NDA, NWS 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.
Uranium enrichment	Continues until 2039
SF reprocessing	Magnox fuel reprocessing came to an end in July 2022 (55,000 tU in total) All reprocessing facilities fully decommissioned by 2090 4,530 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 2024
Harwell & Winfrith	All redundant facilities are fully decommissioned by 2054
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 waste destined for a GDF is produced in the manufacturing process)

[15] Excludes wastes managed under Scottish Government's Policy for higher activity radioactive waste [10].

[16] Since the preparation of the 2022 IGD this has been extended to 2026 [32]

A.2 Assumptions regarding quantities

Table A-2. The estimated contents of each waste group.

Waste Group	Assumptions[17]
SILW / SLLW UILW / ULLW RSCs	All 2022 UK Inventory ILW, excluding those wastes with an expected management strategy of incineration, recycling or disposal at the Low Level Waste Repository (LLWR) All 2022 UK Inventory LLW unsuitable for disposal at the LLWR
DNLEU	198,000 tU from civil fuel enrichment and civil spent fuel reprocessing 9,000 tU from defence programmes
NB SILW NB UILW	ILW from a 24 GW(e) nuclear new build programme
HLW	All 2022 UK Inventory 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: • 1,020 tU Sizewell B PWR SF SF to be managed by NDA: • Oxide: 4,530 tU AGR SF • Magnox (assumed): 1,040 tU metallic SF • Exotic SF manged by NDA: o 68.1 tU Steam Generating Heavy Water Reactor (SGHWR) SF o 21.0 tU Windscale Advanced Gas-cooled Reactor (WAGR) SF o 69.0 tU miscellaneous Light Water Reactor (LWR) SF o 8.21 tHM Prototype Fast Reactor (PFR) SF Fuel not quantified: • Irradiated submarine fuel
NB SF	21,000 tU New Build SF
MOX SF	1,390 tHM MOX SF (includes fuel made from defence Pu) 8%wt Pu
HEU	1.0 tU from civil programmes
Pu	5.75 tHM separated Pu residues from reprocessing of civil SFs (representing 5% of the 115 tHM UK owned Pu unsuitable for re-use as MOX fuel)

A.3 Priority materials and radionuclides

Priority materials and radionuclides in the IGD were established through discussions with NWS safety case owners and experts in the areas of inventory, wasteform, packaging, transport,

[17] Excludes wastes managed under Scottish Government's Policy for higher activity radioactive waste [10].

criticality and GDF design. The priorities were originally established for the 2004 IGD and the assignments have been reviewed for each 'full' update since.

The review of the IGD priorities ahead of the 2022 IGD did not identify any changes to the assignments since the last full update (based on a stock date of 2013). The priority materials are shown in Table A-3 to Table A-7 and the radionuclides in Table A-8.

The identification of priorities allows there to be a focus on enhancements of the inventory data that are most important to NWS. The priority materials and radionuclides do not reflect the coverage and quality of data in the IGD, nor whether a credible means of improving the data within work programme constraints is available.

Table A-3. Material priorities (metals and alloys).

Material	Material
Stainless steel	Magnox / Magnesium
Other ferrous-based alloys	Nickel
Iron	Uranium
Aluminium	Zinc
Beryllium	Zirconium / Zircaloy
Cobalt	Cadmium
Copper	Mercury
Lead	

Table A-4. Material priorities (organics).

Material	Material
Total cellulosics	Organic ion exchange materials
Paper and cotton	Oil or grease
Wood	Other hydrocarbons
Halogenated plastics	Other organics
Total non-halogenated plastics	Polyethylene and polypropylene
Condensation polymers	PVC
Other non-halogenated plastics	Styrene divinyl benzene

Table A-5. Material priorities (other materials).

Material	Material
Graphite	Nickel all forms
Asbestos	Plutonium all forms
Uranium all forms	Ruthenium all forms
Iron all forms	Yttrium all forms
Antimony all forms	Chromium all forms
Beryllium all forms	Ammonium
Niobium all forms	Non-aqueous phase liquids (NAPLs)
Cobalt all forms	Eutectics
Magnesium all forms	Other inorganics
Manganese all forms	

Table A-6. Material priorities (Inorganic anions).

Material	Material
Fluoride	Sulphate
Nitrate	Borate
Nitrite	Other anions
Phosphate	

Table A-7. Material priorities (Hazardous substances / non-hazardous pollutants).

Material	Material
Phenol	Selenium
Styrene	Chromium
Vinyl chloride	Molybdenum
Arsenic	Tin
Cadmium	Vanadium
Caesium	Mercury compounds

Table A-8. Radionuclide priorities[18].

Radionuclide	Radionuclide
C14	Cs135
Cl36	Cs137
Co60	U233
Se79	U235
Kr85	U238
Tc99	Np237
I129	

A.4 Legacy wastes

A.4.1 Bulk material composition

Level 1 and Level 2 materials

The UK Inventory includes numerical data (in terms of percentage by mass) for the contribution of a number of bulk materials (comprising metals, organics, inorganics and others) to the total mass of waste. Table A-9 lists these materials.

There is some overlap between these bulk materials (e.g. Cellulose (total), Cellulose (paper & cotton) and Cellulose (wood)). This is because there are two levels of bulk materials:

- Level 1 materials: such as Cellulose (total) and Rubber (total)

[18] 112 radionuclides have been identified as being relevant to geological disposal [6]. All 112 'relevant' radionuclides are important, and their activities are included in the IGD. A priority score from 1 to 5 was assigned to each radionuclide according to its importance to users of the IGD, with 1 being the most important. To allow a manageable quantity of data to be presented in the IGD reports, only the priority 1 radionuclides are reported.

The sum of the mass of all level 1 materials within a waste stream should[19] equal the total mass of the waste stream

- Level 2 materials: such as Cellulose (paper & cotton) and Halogenated rubber, which are components of Level 1 materials

  The sum of all level 2 materials that comprise a level 1 material should equal the mass of the level 1 material in that stream

The sum of all level 1 and level 2 materials within a waste stream will be greater than the total mass of the waste stream due to double counting.

Table A-9 contains the bulk components reported numerically in the 2022 UK Inventory for legacy waste; there are other materials not listed here that could be in the waste. However, contextual descriptive fields are reviewed for each waste stream in the UK Inventory for additional materials to be quantified in the IGD. This review and enhancement process is detailed in the following section.

[19] Note: the word should is used as although UK Inventory submissions should adhere to these rules, not all streams can, or do, for various reasons. The review and enhancement process of turning “should equal” to “equal” is described in Appendix A.4.2, although it is not always possible depending on the information submitted to the UK Inventory.

Table A-9. Chemical components for which the 2022 UK Inventory contains numerical data.

Meals and alloys	Organics	Inorganics
Aluminium	Total cellulosics	Asbestos
Beryllium	Paper and cotton (cellulosics)	Non-low friable (asbestos)
Cobalt	Wood (cellulosics)	Moderately friable (asbestos)
Copper	Halogenated plastics	Highly friable (asbestos)
Iron	Total non-halogenated plastics	Brick/stone/rubble
Lead	Condensation polymers (non-halogenated plastics)	Cementitious material
Magnox/magnesium	Others (non-halogenated plastics)	Desiccants/Catalysts
Nickel	Rubber total	Free aqueous liquids
Other ferrous metals	Halogenated rubber (rubber)	Free non-aqueous liquids
Stainless steel	Non-halogenated rubber (rubber)	Glass/Ceramics
Titanium	Hydrocarbons	Graphite
Uranium	Oil or grease (hydrocarbons)	Inorganic ion exchange materials
Zinc	Fuel (hydrocarbons)	Inorganic sludges and flocs
Zircaloy/zirconium	Asphalt/Tarmac (cont. coal tar) (hydrocarbons)	Powder/Ash
Other metals	Asphalt/Tarmac (no coal tar) (hydrocarbons)	Sand
	Bitumen (hydrocarbons)	Soil
	Organic ion exchange materials	
	Others (hydrocarbons)	
	Other organics	

A.4.2 Review and enhancement methodology

Legacy ILW/LLW

The review and enhancement methodology is a stepwise approach that aims to provide data in the required format by taking qualitative UK Inventory and, “where appropriate”, making quantitative assumptions. The methodology is detailed below:

1. Use is made of numerical data for the material components (wt %). Prefixes and supporting descriptive data fields for each waste stream are compiled.

2. To specify the presence of material components in the UK Inventory where the quantity is unknown, the prefixes P (present) or TR (present at trace levels) are used by waste producers in data submissions:

    - for cases where P is reported for a material, supporting descriptive data fields and similar waste streams are reviewed in an attempt to quantify the material component

    - for cases where TR is reported for a material, no enhancement is made. The justification is that the UK Inventory conventions define ‘TR’ as in the range 1 – 100 ppm. A review of the data in the 2022 UK Inventory showed that applying

this methodology would only add ~6 tonnes to the total mass of legacy ILW (i.e. ~0.003%). Because the impact is small, and well within the uncertainties on the waste masses, the enhancement is judged to be unnecessary.

3. Numerical data are supplemented by reviewing the supporting descriptive data fields in the UK Inventory to identify any Level 1 materials in Table A-9 that are described but not quantified. All waste streams are screened to capture any Level 1 material components.
4. Waste streams containing ion exchange resins and sludges are reviewed to ensure that free aqueous liquid is not double counted (i.e. if its percentage by weight is reported separately it is not also reported as part of the percentage by weight of the resin / sludge).
5. Data for waste streams where only total values are given for metal, inorganics or organics, or where cellulose, plastics or rubbers are not split into their component parts, are analysed. If there are no supporting descriptive data or surrogate waste streams to allow specific data enhancements for these streams, assignments are made based on relative masses of these materials that are quantified in the UK Inventory.
6. Numerical Level 1 material component values of each stream are summed to identify streams where Level 1 materials do not sum to 100% of the total mass of the stream.
7. Waste streams with the greatest unassigned mass are identified. Generally, most of the unassigned mass in the UK Inventory is associated with a small number of waste streams; the focus of the enhancements is on these waste streams. Supporting descriptive data fields and comparison with similar waste streams in the UK Inventory are used to enhance the data. The aim is to assign > 99% of the total waste mass.
8. Priority materials are enhanced using the following process:
    - incorporate existing enhancements from previous IGD
    - compare latest UK Inventory and previous IGD material composition descriptive data fields to confirm existing enhancements or to incorporate new or updated data
    - review the descriptive data fields for those waste streams in the latest UK Inventory that are not in the previous IGD and incorporate any data
9. Any mass not allocated to a specific material remains unassigned.

HLW

HLW streams are made up of calcined waste oxide in a borosilicate glass matrix within stainless steel WVP canisters, with the exception of high level contaminated plant items (stream 2F22/C), which comprise Inconel and stainless steel in a borosilicate glass matrix within WVP canisters.

The material composition and bulk density of each HLW stream as reported in the UK Inventory do not include the stainless steel WVP canister and only describe the waste form. HLW streams are enhanced to include the additional stainless steel mass of the WVP canister, and to revise the stored mass, volume and density.

The UK Inventory reports that each WVP canister contains 0.15 m^3 of vitrified HLW with a density of 2.65 t/m^3. Thus the mass of the vitrified product is approximately 400 kg. Typically the mass comprises approximately 100 kg of waste oxide and approximately 300 kg of borosilicate glass although more recent batches have a higher waste oxide content[20].

[20] Due to process improvements the waste loading has increased from an initial typical waste oxide incorporation rate of 25%, with 98% of Magnox HLW containers having a waste oxide

The composition assumed for the glass is given in Table A-10 from information in the UK Inventory. The WVP canister has a mass of about 85 kg and is manufactured from Type 309 stainless steel.

Table A-10. Composition of the glass used to vitrify HLW (%).

Material	SiO_2	Na_2O	B_2O_3	Li_2O
Glass	62.8	11.5	23.0	2.7

A.4.3 Elemental composition

Material grades and types are assigned to all bulk materials and elemental compositions / specifications for these bulk materials are then used with the material masses to derive elemental masses.

The approach is detailed below.

1. Allocate material grades to steels, other metals and alloys and to proprietary material types such as ion exchange resins using the following order of preference:
    - data reported in the UK Inventory
    - IGD enhancements
    - additional available information
2. Where the total mass of a material component in a waste stream is made up of several different grades (e.g. stainless steel), assign proportions to each grade.
3. Where specific material grades or types are not reported and no information is available it is assigned as a mix of grades or types. These assignments are made in the same relative proportion as major contributing streams where grades are reported.
4. Once material grades have been established for all of the components, the elemental masses are determined using a database of elemental precursor compositions (see *Elemental composition*)

A.4.4 Radionuclide composition

The latest UK Inventory data are the starting point for developing the IGD radionuclide compositions for legacy HLW, ILW and LLW streams.

The data review aims to identify issues for enhancement (for example, potential anomalies, missing data and under-reporting). All issues for enhancement are addressed and prioritised for feeding back potential improvements to the next UK Inventory.

The following methodology is used.

1. Use the priority scores of radionuclides as a guide for the level effort to apply in the review and enhancement work.
2. Identify other additional sources of public domain data (e.g. reports from NWS's Integrated Project Teams).
3. For each radionuclide, order waste streams by contribution and carry out a sanity check to identify if any waste streams have a significantly (order of magnitude) lower or higher activity

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incorporation rate of up to 30% and 2% of containers having a waste oxide incorporation rate of 30-34%.

than would be expected based on activities found in similar waste streams. Investigate any discrepancies and make necessary adjustments by:

- analysing any changes to the stream from the previous inventory
- consulting with the waste producer
- revising data if necessary
- documenting the change and reasoning in an audit trail
- adding the data item to the waste producer's improvement plan for the next UK Inventory

4. Identify gaps in the data for waste streams that do not contribute to radionuclide totals (because activity is not quantified). Disregard gaps for small volume waste streams that contain insignificant activities.
5. Focus enhancement work on the more significant gaps in activities (i.e. for each radionuclide consider those waste streams likely to have higher activity). For example, gaps for fission products and actinides in Sellafield waste streams and gaps for activation products in reactor waste streams.
6. Where appropriate, fill gaps by using the previous IGD enhancements:
    - for waste streams with an unchanged radionuclide composition, use previous IGD values (subject to decay adjustments for stocks).
    - for waste streams with a revised radionuclide composition, factor previous IGD values by selecting a marker (pertinent radionuclide or total).
7. Fill remaining gaps by using the latest UK Inventory radionuclide composition data:
    - for waste streams with no quantified activity values, select a surrogate waste stream that is expected to have a similar radionuclide composition.
    - for waste streams with only total activity quantified, select a surrogate waste stream that is expected to have a similar radionuclide composition and calculate radionuclide activities by factoring using total activity.
    - for waste streams with an incomplete radionuclide composition, select a surrogate waste stream that is expected to have a similar composition and calculate radionuclide activities by factoring using a marker radionuclide.
8. Derive activity values where a radionuclide has a 'Code 7'[21] reported in the UK Inventory. Select a surrogate waste stream that is expected to have a similar radionuclide fingerprint and calculate radionuclide activities by factoring using a marker radionuclide.
9. A final check of the radionuclide activity data is carried out. This includes the calculation of total radionuclide activity changes and a review of radionuclide ratios.

A.5 Legacy SF

The UK Inventory includes only masses of legacy SF. For each fuel type, the material and radionuclide inventories need to be calculated and a packaging concept assigned.

[21] Activities of radionuclides are reported in the UK Inventory with an associated code to indicate how the data have been produced (e.g. calculated or measured). A 'Code 7' is reported when a radionuclide is known to be present in significant quantities but a value has not been determined.

Radionuclide inventories for these fuels have been calculated using the outputs from internationally recognised software (e.g. FISPIN, FISPACT and ORIGEN). The assumed key input parameters (material composition, enrichment, burn-up and cooling time) for each fuel type are listed in the relevant subsection below.

The following approach was adopted for deriving the radionuclide inventories:

- use inventories NWS has adopted for other work or use the most recent data / calculations publicly available
- use the most appropriate fuel burnups, but without underestimating likely SF radionuclide inventories
- use existing fuel burnup data (rather than carry out new calculations)
- revise radionuclide activities which have been derived from outdated nuclear data libraries and have changed significantly (this is particularly relevant for the half-life of Se-79)

The specific activity data for SF streams have been taken from several sources. These are based on the use of fresh (i.e. not recycled) uranium for fuel manufacture, and an appropriate burnup for each fuel type.

The characterisation of the legacy SF is frequently reviewed and the data presented in the following section represents the current assumptions.

A.5.1 Oxide (AGR)

Bulk materials

Spent fuel bulk materials are quantified for each type of disposal container. Table A-11 presents the assumed fuel composition. More details of the packaging assumptions are provided in Appendix B.2.1.

Table A-11. AGR SF components in a disposal container.

Component	Material	Mass (t)
Fuel	UO_2	2.34 (=2.06 t U)
Cladding	Type 20/25 Nb SS	0.282
Sintox discs	Al_2O_3	0.016
Slotted cans	Type 316 SS	0.197

Elemental composition

SF irradiated compositions are used for the UO_2. However, for the fuel cladding, a pre-irradiation elemental composition is used (analysis of the impact of irradiation on fuel cladding and component compositions shows that there are no significant changes in elemental masses).

Radionuclide inventories

It is assumed that the SF remaining unreprocessed is that which has been most recently discharged from reactors. It is assumed that AGR fuel, in stock and until all AGRs shutdown, can be divided into two enrichments (3.2% and 3.78%), each with a burn-up of 33 GWd/tU.

The other irradiated components of the AGR SF that are disposed of with the UO_2 are assumed to be irradiated to 33.33 GWd/tU. In addition, the impurities in the components and fuel are assumed to be present at the upper end of the distribution.

Table A-12. The key parameters used in the calculation of AGR SF radionuclide inventory.

Fuel	Burn-up (GWd/tHM)	Enrichment (%)	Assumed Arising Date(s)
AGR Spent Fuel	33	3.78% and 3.2%	1998 to 2022 (stocks, uniformly) Arisings 2022 to 2024 for four stations and 2024 to 2028 for two stations

A.5.2 Magnox

Bulk materials

The data (including quantities, materials and radionuclide inventory) for Magnox SF are based on populations of SF stored at the Sellafield site. The characterisation is frequently reviewed and the information presented below represents the current assumptions.

Details of representative materials and masses typically contained within a single disposal container (corresponding to 26 intact fuel elements in each of three WVP-type canisters) are given in Table A-13. The fuel and cladding data are average values for the waste expected to be disposed of. More details of the packaging assumptions are provided in Appendix B.2.1.

Table A-13. Bulk materials in a typical Magnox disposal container.

Material	Mass (t)
Uranium	0.886
Magnox Al80	0.159
Stainless steel	0.381

Elemental composition

The elemental composition of the uranium fuel is taken from a radionuclide inventory calculation for Magnox SF (with a burn-up of 4.1 GWd/tU). A pre-irradiation elemental composition is used for the fuel cladding.

Radionuclide inventories

The radionuclide composition of the Magnox SF have been calculated using inventories available from other NWS work. NWS's standard toolkits consider low burn-up Magnox fuel to natural uranium (i.e. an enrichment of 0.71 wt% U-235) with a burn-up of 4.1GWd/tU[22].

A.5.3 Exotic

Bulk materials

Spent fuel bulk materials are quantified for each type of fuel and its assumed disposal container. Table A-14 to Table A-15 presents the assumed fuel compositions for WAGR and SGHWR SF, which are assumed to be disposed of in AGR disposal containers. Table A-16 presents the assumed fuel compositions for miscellaneous LWR SF, which is assumed to be disposed of in PWR disposal containers. Table A-17 presents the assumed fuel compositions

[22] The Magnox SF in the inventory will have a range of enrichments and burn-ups, but it is assumed that the majority will be natural uranium with a low burn-up.

for the PFR SF, in which seven SF containers are assumed to be disposed of per PFR disposal container. More details of the packaging assumptions are provided in Appendix B.2.1.

Table A-14. Typical WAGR SF components in a disposal container.

Component	Material	Mass (t)
Fuel	UO_2 (of which U)	2.34 (2.06 = U)
Cladding	Type 20/25 Nb stainless steel[23]	0.282
Slotted cans	Type 316 stainless steel[24]	0.197

Table A-15. Typical SGHWR SF components in a disposal container.

Component	Material	Mass (t)
Fuel	UO_2 (of which U)	2.34 (2.06 = U)
Cladding	Type 20/25 Nb stainless steel	0.282
Slotted cans	Type 316 stainless steel[25]	0.197

Table A-16. Typical Miscellaneous LWR SF components in a disposal container.

Component	Material	Mass (t)
Fuel	UO_2 (of which U)	2.08 (1.83 = U)
Cladding	Zircaloy 2	0.4688
Plenum springs, Grid sleeves, Top & bottom nozzles	Type 304 Stainless steel	$6.48\ 10^{-2}$
Grids	Inconel 718	$2.68\ 10^{-2}$

Table A-17. Typical PFR SF components in a disposal container.

Component	Material	Mass (t)
Fuel	UO_2/PuO_2 (U / Pu)	0.56 (0.49)
Cladding, wrapper and furniture	Nimonic	0.26
Cladding, wrapper and furniture	Stainless steel (mixed grades)	0.75

Elemental composition

SF irradiated compositions are used for the UO_2. However, for the fuel cladding, a pre-irradiation elemental composition is used (analysis of the impact of irradiation on fuel cladding and component compositions showed that there are no significant changes in elemental masses).

Pre-irradiation elemental compositions are used for PFR. NWS considers that the significantly lower mass of PFR SF when compared with the other legacy SF does not justify developing estimates for irradiated fuel compositions.

[23] WAGR spent fuel pins are clad in stainless steel or beryllium; for the 2022 IGD they were all assumed to be clad in stainless steel.

[24] Not irradiated.

[25] Not irradiated.

Radionuclide inventories

The radionuclide compositions of the SF have been calculated based on the parameters given in Table A-18.

Table A-18. The key parameters used in the calculation of WAGR, SGHWR and miscellaneous LWR SF radionuclide inventory.

Fuel	Burn-up [GWd/tHM]	Enrichment [%]	Assumed Arising Date(s)
WAGR spent fuel	18.2	2.85	1981
SGHWR spent fuel	40	3.9	1990
Misc. LWR spent fuel	40	3.9	2000

A.5.4 Oxide (PWR)

Bulk materials

Table A-19 presents representative material masses for the bulk materials in a disposal container. More details of the packaging assumptions are provided in Appendix B.2.1.

Table A-19. Typical PWR SF components in a disposal container.

Component	Material	Mass (t)
Fuel	UO_2 (of which U)	2.08 (1.83=U)
Cladding	Zircaloy 4	0.469
Grids	Inconel 718	$2.68\ 10^{-2}$
Plenum springs, nozzles & sleeves	Stainless steel (Type 304)	$6.48\ 10^{-2}$

Elemental composition

SF irradiated compositions are used for the UO_2. However, for the fuel cladding, a pre-irradiation elemental composition is used (analysis of the impact of irradiation on fuel cladding and component compositions showed that there are no significant changes in elemental masses).

Radionuclide inventories

Sizewell B SF assemblies are assumed to be disposed of intact and it is necessary to include the contribution to the inventory from the non-fuel components of the fuel assembly; these are detailed in Table A-19. As with the AGR SF, the impurities in the components and fuel are assumed to be present at the maximum permissible level. The components and impurities are assumed to be irradiated to 45 GWd/tU.

Table A-20. The key parameters used in the calculation of PWR SF radionuclide inventory.

Fuel	Burn-up (GWd/tHM)	Enrichment (%)	Assumed Arising Date(s)
PWR Spent Fuel	4.5	4.6	1995-2035

A.6 Uranium and plutonium

The UK Inventory includes only masses (in tonnes of heavy metal) of uranium and plutonium; material and radionuclide compositions need to be calculated and assigned a packaging concept for each waste stream.

A.6.1 Uranium

Bulk materials

Uranium is stored in several different chemical forms; principally as an oxide or a fluoride. However, it is assumed that uranium is converted to its oxide form for disposal. Each uranium stream is reviewed for its nature and available characterisation data.

Table A-21. Uranium waste streams in the 2022 IGD.

Waste Group	Description	Assumed chemical form for disposal
HEU	HEU from civil nuclear programmes	UO_2
DNLEU	THORP Product Uranium	U_3O_8
DNLEU	Depleted Uranium from Defence	UO_3
DNLEU	Miscellaneous DNLEU – LEU residues	U_3O_8
DNLEU	Miscellaneous DNLEU – LEU metal billets	U_3O_8
DNLEU	Miscellaneous DNLEU – Natural uranium residues	U_3O_8
DNLEU	Miscellaneous DNLEU – DU residues	U_3O_8
DNLEU	MDU (in overpacked 200 litre mild steel drums)	UO_3
DNLEU	MDU (in 210 litre stainless steel drums)	UO_3
DNLEU	DU Tails	U_3O_8
DNLEU	Uranium Tetrafluoride	U_3O_8
DNLEU	DU Tails (Unirradiated) in DV-70 (from Defence)	U_3O_8

It is assumed that HEU for disposal is currently in the form of UO_2, and that DNLEU will be in the form of U_3O_8 or UO_3 depending on its origin, as shown in Table A-21. The bulk material composition of the wasteform is therefore assigned to heavy metal (uranium) oxide. For the DNLEU streams to be disposed of in Uranium TDCs however, the waste is (or will be) stored in a primary container prior to transport and disposal. The waste is disposed of in the primary containers, which are assumed to be overpacked in TDCs. For these streams the bulk material composition includes the primary containers and other internal packaging materials, which are classed as part of the wasteform.

Elemental composition

The elemental composition of uranium waste is that of the bulk wasteform (predominantly uranium) with the addition of impurities. Impurities are added based on the investigation below:

- No information has been identified on chemical impurities in HEU. As these are likely to be at very low levels, and therefore of no significance, no impurities are included.
- The uranyl fluoride (UO_2F_2) content of material deconverted from uranium hexafluoride (UF_6) tails derived from unirradiated uranium has been assumed to be 4 wt% which is expected to be a conservatively high value.
- No information has been identified on the likely chemical composition of the deconverted U_3O_8 product originating from irradiated uranium, but the composition is assumed to be the same as that originating from unirradiated uranium. No published data on the level of technetium has been identified. A value of approximately 1 ppb has been assumed.
- The MDU UO_3 specification for recycled material [18] provides limits on some contaminants (see Table A-22). These are used to derive an improved composition. In

the absence of any other published material data, these bounding values are also used for the THORP Product Uranium (TPU) composition.

- No references have been identified that give information on the trace chemical levels in miscellaneous DNLEU streams. As these are likely to be at very low levels, and therefore of no significance, no assumptions have been made.

Table A-22. MDU UO_3 specification.

Contaminant	Concentration (µg / gU)
Iron	< 300
Sodium	< 20
Nitrate (as NO_3)	< 8,000
Sulphate (as SO_4)	> 950 & < 1,450

For the internal packaging materials of the uranium TDC streams, typical steel alloy compositions are assumed based on similar internal containers used for ILW.

Radionuclide inventories

The isotopic composition of uranium and the presence of impurities are different for uranium that has arisen from reprocessing spent fuel and uranium that has arisen from the enrichment of natural uranium. For material separated from irradiated fuel, the determining factors are the reactor type, the initial enrichment of the uranium in the fuel, the discharge burn-up and the decontamination factors during reprocessing.

Small quantities of impurities, including plutonium and fission products, are likely to have been carried over into the MDU and TPU streams during the chemical separation phase of reprocessing. The radioactivities of these impurities are calculated by applying mean whole plant decontamination factors to the specific plant used for separating radionuclides during reprocessing. A subsequent period of radioactive decay is applied; this is the estimated average age of material accumulations assuming constant arisings over time.

Published decontamination factors (DF) are available for the THORP reprocessing plant only [19] (see Table A-23). These factors have also been used for determining radionuclide impurity levels in MDU. The midpoint DFs have been applied to other radionuclide species by selecting the value for the contaminant that is likely to show a similar chemical behaviour during reprocessing.

Table A-23. Observed contaminant decontamination factors (DF) for THORP (whole plant to UO_3 product) from [19].

Contaminant	Observed DF to UO_3 product	Midpoint DF
Tc-99	$8.17\ 10^3$ – $1.16\ 10^4$	$9.89\ 10^3$
Ru-106	$4.32\ 10^6$ – $1.33\ 10^7$	$8.81\ 10^6$
Cs-134 + Cs-137	$5.66\ 10^9$ – $1.38\ 10^{10}$	$9.73\ 10^9$
Ce-144	$9.36\ 10^5$ – $4.96\ 10^6$	$2.95\ 10^6$
Np-237	$3.31\ 10^4$ – $6.76\ 10^4$	$5.04\ 10^4$
Plutonium isotopes	$8.60\ 10^6$ – $2.03\ 10^7$	$1.45\ 10^7$

Depleted uranium tails generated from the use of irradiated MDU in the enrichment process contain the artificial isotopes U-232 and U-236. The fate of fission products (principally technetium) and transuranics (principally neptunium and plutonium) when MDU was

reconverted and re-enriched is complex. Estimates of U-232, U-234, U-235, U-236 and U-238 specific activities were quantified from the UK Inventory.

Some depleted uranium tails produced from natural, unirradiated UF_6 will also be contaminated with U-232 and U-236 because, in the past, they were sometimes collected in emptied (but not washed out) feed cylinders that had previously been used for MDU-derived material, resulting in cross-contamination. The levels of contamination are not known but are likely to be very low and therefore no estimate has been made for the IGD.

A.6.2 Plutonium

Bulk materials

The IGD includes some separated civil plutonium (which is assumed not to be suitable for re-use as MOX fuel) for geological disposal; this material is stored as solid PuO_2 powder. Therefore, the material composition of the waste is heavy metal (plutonium) oxide.

Elemental composition

Plutonium is separated from the uranium, transuranic elements and fission products in spent fuel by a process of solvent extraction. The multiple cycles of solvent extraction ensure that the plutonium stream has a high degree of chemical purity.

The only information on impurities and their levels in separated plutonium indicates that uranium, fission products and non-volatile oxides in PuO_2 from spent oxide fuel reprocessing in THORP are present at very low levels. There may also be residual chemical species (e.g. nitrate) and trace metallic species from the corrosion of process equipment (e.g. iron and nickel from stainless steel). While contamination as a result of storage is likely to be present in pre-1980 PuO_2, their levels are unknown and are not quantified.

Radionuclide inventories

The isotopic composition of separated plutonium is determined by reactor type, the initial enrichment of uranium in the fuel, the discharge burn-up and the duration of radioactive decay since discharge from the reactor.

The civil plutonium residues unsuitable for MOX fuel production (stream MPu001) are assumed to be older material from Magnox fuel reprocessing. This material has comparatively good isotopic quality (i.e. less Pu- 241). However, there will be a degree of americium from ingrowth during storage. The discharge plutonium isotope composition adopted is based on Magnox fuel with a burn-up of 3 GWd/tU and 1 year cooled. The period of accumulation is assumed to be 1957 – 1961.

Small quantities of uranium and other species are likely to have been carried over into the plutonium stream during the chemical separation phase of SF reprocessing. The radioactivities of these impurities are calculated from typical SF compositions (i.e. the initial composition of the feed to the chemical separation plant) and reported mean decontamination factors that quantify the performance of the plant [20]. The following decontamination factors are used:

- uranium (to PuO_2) 10^7
- fission products 3×10^8

A.7 New build

The term “new build” is used to cover reactors that are not yet currently operational (Hinkley Point C therefore counts as a new build reactor site). The inventory will be sensitive to the size, composition and timing of a new build programme: the size will determine the total quantity of

waste; the composition will determine the materials used; and the timing will affect the activity of the waste produced.

A.7.1 ILW

Operational and decommissioning streams

The operational waste destined for geological disposal from all the assumed new build reactors is taken from the four ILW streams from the Hinkley Point C site which are included in the 2022 UK Inventory. The volume and proposed packaging of operational wastes for Sizewell C were developed by analogy with Hinkley Point C, with SMR/AMR sites scaled to a per-gigawatt inventory. The per GW(e) streams were developed by dividing the information by the electrical output of an EPR (1.6 GW(e) per reactor).

Three ILW streams were considered as part of the GDA assessment of disposability arising from decommissioning activities for a UK EPR [16].

The new-build inventory information was reviewed and enhanced as per the methodology in Appendix A.4.2.

Materials composition

The approach to establishing the material composition of the new build wastes is:

1. Use material components and grades given in the 2022 UK Inventory for Hinkley Point C for operational streams and reference documents for the UK EPR **[16, 21]** for decommissioning streams.
2. Where information is not available, assume the same compositions as equivalent streams from the Sizewell B PWR.

Elemental composition

The approach for calculating the elemental composition is the same as that for the bulk composition of the waste. Information is taken from reference documents and, where information is not available for the grade of material, assumptions are made based on similar waste streams in the IGD.

Radionuclide composition

Radionuclide inventories for the operational streams have been taken from the 2022 UK Inventory for Hinkley Point C and subject to the review and enhancement methodology in Appendix A.4.2. The radionuclide inventories for the decommissioning streams have been taken from the GDA disposability assessment report for an UK EPR [21].

A.7.2 Spent fuel

Fuel for the new build reactors is assumed to be manufactured from fresh uranium and will be in the form of enriched UO_2. However, the depleted uranium tails that are associated with the manufacture of the fuel are not included in the IGD (because it is not known if the fuel will be produced in the UK). Instead, the inclusion of additional depleted uranium is considered in alternative scenario B.

The UK EPRs are assumed to discharge fuel with a burn-up of 65 GWd/tU. The radionuclide inventories for the SF have been taken from the GDA reports and, for simplicity, the total arisings of the SF are assumed to be equally distributed over the operational lifetime of the reactors. It is assumed that the SF are disposed of directly, with three SF assemblies in a single disposal container.

The Pre-Construction Safety Report (PCSR) for the proposed Hinkley Point C UK EPR presents the number of SF assemblies for burn-ups of 50 GWd/tU and 65 GWd/tU [22]. 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. For each UK EPR, the IGD includes 870 SF disposal containers. The arisings for 1 GW(e) of SMR or AMR generation were assumed to be (1/1.6) = 0.625 of the arisings for a single EPR.

Materials composition

The material composition of the SF assemblies is given in the GDA disposability assessment reports [16, 21]. Table A-24 shows the mass breakdown of a single EPR fuel assembly.

Table A-24. Material masses (kg) and percentages for a single EPR fuel assembly.

Material	Mass (kg)	Mass fraction
UO_2	598	76.7%
Zircaloy M5	162	20.8%
AISI 304 L Stainless Steel	15	1.92%
Inconel 718	4	0.51%
Al_2O_3	1	0.13%
Total	**780**	**100.00%**

Elemental composition

The material grades and masses reported in Table A-24 are used to calculate the elemental composition of the disposed waste. The fuel is assumed to be unirradiated with no impurities.

Radionuclide composition

Radionuclide inventories for the SF from a new build programme have been taken from the GDA disposability assessment reports. Parameters assumed in calculations are reported in Table A-25 and each reactor lifetime is 60 years. Fuel arisings are split evenly over each year of the lifetime of each reactor.

Table A-25. The key parameters used in the calculation of new build SF radionuclide inventory [16].

Burn-up (GWd/tHM)	Enrichment (%)	Cooling times (yrs)
65	5.0	1

A.8 MOX

To create an illustrative MOX SF inventory, it was agreed with NDA Strategy that NWS assume that MOX fuel is irradiated to 50 GWd/tU in a generic PWR.

A.8.1 Material composition

The illustrative calculations assume that the fuel is irradiated in a PWR. A summary of the material content of a MOX fuel assembly is presented in Table A-26. The material masses were taken by analogy from the GDA disposability assessments for the UK EPR [16] and AP1000 [23]. The heavy metal mass per assembly is taken to be same as the AP1000 whilst materials associated with the cladding and other assembly components are assumed to be the same as the UK EPR. The disposal containers for MOX spent fuel were assumed each to contain one spent fuel assembly.

Table A-26. MOX fuel assembly material masses used for calculations.

Material	Mass per container (t)
UO_2 / PuO_2 (U / Pu)	0.613 (0.540)
Zircaloy M5	0.162
Inconel 718	$4.36\ 10^{-3}$
AISI 304L Stainless Steel	$1.46\ 10^{-2}$
Al_2O_3	$5.95\ 10^{-4}$

A.8.2 Elemental composition

The material grades and masses reported in Table A-26 are used to calculate the elemental composition of the disposed waste; the fuel was assumed to be unirradiated with no impurities.

A.8.3 Radionuclide composition

The composition of the unirradiated fuel is assumed to be as follows:

- 8 wt% plutonium
- the bulk of the fuel will be depleted uranium with an enrichment of 0.3%
- Am241 is present as 3.8 wt% of the mass of plutonium

The calculations for the MOX SF radionuclide inventory were carried out using ORIGEN and assumed a reactor thermal rating of 38 MW/tHM.

While the radionuclide inventory for the SF is appropriate to a burn-up of 50 GWd/tU, the cladding and impurities inventories are based on a burn-up of 61 GWd/tU. The apparent discrepancy between the burn-up assumed for the fuel and that assumed for the other components is expected to be insignificant.

A.9 Gas generation data

A.9.1 Metal geometry data

Many ILW streams contain reactive metals that, through corrosion after disposal, generate gas. The consequences of the release of any gas to the human environment are determined in performance assessment calculations. The principal reactive metals are Magnox, aluminium and uranium. Other metals, including stainless and mild steels and Zircaloy, may also be important because of their large quantities in the wastes. Waste containers also comprise significant amounts of metals (mainly stainless steel, but some cast iron and mild steel are also used).

Mass and geometry information for each of the above metal types is used to analyse the rate of hydrogen production from the waste. Geometry is a determining factor because the exposed surface area of a material affects the rate of gas production.

Legacy waste mass and geometry information is updated from the previous IGD with relevant information from the latest UK Inventory. A simple approach is used to derive a single plate thickness and single sphere thickness for each metal type; this is detailed below.

1. Consider the UK Inventory mass data for stainless steel, mild steel (other ferrous metals), Magnox, aluminium, Zircaloy and uranium.
2. For each metal type, rank the streams by mass with the highest contributors to the total mass first. The top contributor streams are selected from the list until 90% of the mass is accounted for; only these streams are examined further.

3. Where waste stream properties are the same as in the previous IGD the existing calculated geometry and material thickness is retained.
4. Where new waste streams are included in the top contributors, or where waste stream properties are different, geometry and material thickness data are derived by examining the UK Inventory data, comparing physical properties against analogous streams with similar geometry and applying expert judgement.
5. An average thickness / radius is calculated using a weighted average for each material in each waste group.
6. The results are scaled up to account for 100% of the material masses by assuming that the average effective plate thicknesses, sphere radii and plate to sphere ratio determined for those streams comprising 90% of the mass are indicative of the whole.

In addition, the metal content of waste disposal containers is considered. Certain waste containers are manufactured from stainless steel or cast iron (see Appendix B: Waste containers). The stainless steel stillages disposed of with the 500 l drums are also taken into account.

For HHGW streams the metal content of the waste disposal containers is considered. The corrosion of HHGW itself is not considered in the calculations as the waste is contained in thick-walled disposal containers which will have significant durability in the disposal environment.

As the UK Inventory does not contain waste streams from new build reactors[26], the methodology is to review publicly available reference material and, if no data can be found, to adopt the equivalent data for Sizewell B waste streams.

A.9.2 Breakdown of H-3 and C-14 by material type

A feature of ILW and LLW streams is that they contain materials that produce gas when they corrode, degrade or interact with radiation. Thus gas is generated by corrosion of metals, degradation of organic wastes (particularly cellulose) and by radiolysis. The most important gases volumetrically are hydrogen, carbon dioxide and methane. A small proportion of the gas generated can be radioactive, containing H-3 and C-14.

As part of the assessment of the gas pathway, an analysis of the material types associated with H-3 and C-14 inventories in wastes within the IGD is carried out. This information provides an important input to calculations to determine the rate of gas generation from ILW and LLW in the GDF environment. Since the current assumption is that the GDF will close in 2200, activities are considered at 2200.

A.9.3 Method to calculate C-14 by material type.

The approach to the analysis comprises the following stages:

1. Rank waste streams in order of total C-14 activity. Priority is given to streams that are the major contributors to the total C-14 activity.
2. Assign streams to a list of 12 material types (shown in Table A-27).
3. Where there is more than one material type associated with significant fractions of C-14 activity, methods are used to apportion the total stream activity between the material types.

[26] With the exception of operational waste from the Hinkley Point C site.

Table A-27. Material types used in the breakdown of C-14 activity.

Material code	Material description
G	Graphite
SS	Stainless Steel
MS	Other ferrous based alloys most likely to be low carbon / mild steel
Z	Zircaloy and Zirconium
NIM	Nimonic (nickel based) alloys such as Nimonic PE16 & 80A
MX	Magnox alloys AL80, ZR55, MN80, MN150
U Uranium metal	Uranium metal
MX – corroded	Magnox alloy corrosion products most likely to be $Mg(OH)_2$
U – corroded	Uranium metal corrosion products, i.e. UO_x
Non Metal	Materials such as desiccant, ion exchange resin and barium carbonate arising from THORP operations
GEH	Specific GE Healthcare waste stream rich in C-14
N/A	Not Assessed

Method A: When the waste stream contains more than one activated material

The apportioning of C-14 activity assumes that this activity is generated by the thermal neutron activation of the nitrogen impurity content of the materials. This is calculated from the product of three factors:

- M: the fraction of the waste stream associated with the material
- N: the concentration (in ppm) of nitrogen in the material (the assumption is that C-14 is primarily produced by the N-14(n,p)C-14 activation route)
- F: the relative thermal neutron flux to which the material is exposed

The material fractions, M, are obtained from inventory waste stream data. The nitrogen concentration values, N, were largely taken as the 50th percentile values derived from the upper and lower bound precursor concentration data. The relative thermal flux data were derived in several ways, as follows:

- where all materials are irradiated in the fuelled region of the reactor core, F is taken as unity for all material types.
- for AGR stringer debris streams that contain Nimonic PE16 tie bars that pass through the fuelled core region, and also graphite and steel components from outside the fuelled regions, Cl-35(n,γ)Cl-36 activation rates, developed for Nirex's Cl-36 project [24], were used as a surrogate for thermal flux data (such an approach is valid as the energy dependence of the N-14(n,p)C-14 and Cl-35(n,γ)Cl-36 reactions are similar).
- in a small number of cases, such as with the steam generating heavy water reactor decommissioning stream 5G302, where detailed flux or activation rate information is not available but it is known that some of the activated materials have been irradiated in the fuelled core region and others were located just outside this region, F is taken as 0.1 for the ex-core materials and 1.0 for the in core materials.

Method B: Apportioning Magnox and uranium to metal and corrosion products

Several waste streams contain Magnox and / or uranium metal stored under water. In such cases these reactive metals undergo corrosion to oxide and / or hydroxide forms. The UK Inventory generally does not quantify the fraction of uranium and Magnox metal that has been

subject to corrosion while in wet storage. However, for the MSSS streams, a quantification is provided. For these waste streams the fractions of corrosion products are used to apportion the amounts of C-14 between remaining metal and corrosion product.

Since the MSSS streams contain both Magnox and uranium metal, it is necessary to first apply Method A to estimate the fraction of the total stream activity initially present in the form of Magnox and uranium metal. These initial metal totals were then apportioned between the remaining metal and corrosion product according to the corrosion factors (see Table A-28).

Estimates are developed where waste streams contain irradiated U and Magnox metal but do not have C-14 activity values.

When the total C-14 activity associated with a waste stream is small, and it was not clear what material type the C-14 is associated with, the activity contribution is assigned to a 'Not Assessed – N/A' category (the activity associated with the N/A waste streams amounted to less than 1% of the total C-14 activity in the 2022 IGD).

Table A-28. The fraction of the reactive metals that are corroded in the 2022 IGD.

Waste Stream ID	Material	Uncorroded (% of stream)	Corroded (% of stream)	Uncorroded + corroded (% of stream)	Corrosion factor [corroded / (uncorroded + corroded)]
2D08.1	Magnox	2.8	35.1	37.9	0.927
2D08.2	Magnox	3.2	41.8	45.0	0.929
2D08.3	Magnox	3.5	46.0	49.5	0.929
2D08.4	Magnox	1.8	21.5	23.3	0.922
2D08.5	Magnox	3.6	48.4	52.0	0.931
2D08.6	Magnox	4.0	47.3	51.3	0.922
2D09.1	Magnox	9.0	38.9	47.8	0.813
2D09.2	Magnox	5.1	49.2	54.3	0.907
2D09.3	Magnox	6.1	48.7	54.8	0.888
2D09.4	Magnox	3.1	30.2	33.4	0.907
2D09.5	Magnox	8.3	38.2	46.5	0.821
2D22.1	Magnox	24.6	7.9	32.4	0.243
2D22.2	Magnox	17.4	22.0	39.4	0.559
2D24.1	Magnox	17.0	22.6	39.6	0.571
2D24.2	Magnox	22.2	16.9	39.1	0.433
2D24.3	Magnox	19.3	21.4	40.6	0.526
2D35.1	Magnox	12.4	2.5	14.9	0.170
2D35.2	Magnox	13.2	2.7	15.9	0.167
2D35.3	Magnox	11.3	2.1	13.4	0.157
2D35.4	Magnox	21.6	4.2	25.7	0.162
2D08.1	Uranium	0.6	1.1	1.7	0.629
2D08.2	Uranium	0.7	1.0	1.7	0.583
2D08.3	Uranium	1.1	2.2	3.3	0.665
2D08.4	Uranium	0.6	0.9	1.5	0.592

Waste Stream ID	Material	Uncorroded (% of stream)	Corroded (% of stream)	Uncorroded + corroded (% of stream)	Corrosion factor [corroded / (uncorroded + corroded)]
2D08.5	Uranium	1.0	2.1	3.1	0.676
2D08.6	Uranium	1.3	2.8	4.1	0.689
2D09.1	Uranium	2.1	3.0	5.1	0.592
2D09.2	Uranium	2.0	3.3	5.3	0.625
2D09.3	Uranium	2.3	3.1	5.4	0.578
2D09.4	Uranium	1.0	2.2	3.2	0.694
2D09.5	Uranium	2.0	2.9	5.0	0.592
2D22.1	Uranium	4.3	2.8	7.1	0.392
2D22.2	Uranium	4.7	3.0	7.7	0.385
2D24.1	Uranium	6.0	3.4	9.5	0.365
2D24.2	Uranium	7.3	4.6	11.9	0.385
2D24.3	Uranium	7.3	4.2	11.5	0.365
2D35.1	Uranium	0.3	0.7	1.0	0.749
2D35.2	Uranium	0.2	0.7	0.9	0.745
2D35.3	Uranium	0.1	0.5	0.6	0.842
2D35.4	Uranium	0.4	1.2	1.6	0.733
9D67	Magnox		100.0	100.0	1.000
9D68	Magnox		100.0	100.0	1.000
9D69a	Magnox		100.0	100.0	1.000
9D69b	Magnox		100.0	100.0	1.000
9D69c	Magnox		100.0	100.0	1.000
9D70a	Magnox		100.0	100.0	1.000
9D70b	Magnox		100.0	100.0	1.000
9D70c	Magnox		100.0	100.0	1.000
9H26/C	Uranium		90.0	90.0	1.000

A.9.4 Method to calculate H-3 by material type

A similar approach to that for C-14 is carried out for H-3. There are a small number of thermal neutron activation reactions with reactor materials and impurities that can result in H-3 production. The principal mode of production is activation of lithium impurities present in uranium fuel and fuel structural materials. The nuclear reaction[27] is Li-6(n,α)H-3.

Tritium exhibits complex behaviour during fuel irradiation and reprocessing. Tritium is particularly mobile and can migrate, for example, through the fuel and fuel cladding. Tritium can also be absorbed by, or react with, solid material surfaces.

[27] Tritium is also produced in significant quantities in fuel as a ternary fission product.

Lithium precursor concentrations in materials present in UK ILW and LLW, subject to thermal neutron activation in reactors, are given in Table A-29. These concentrations are largely 50th percentile values derived from upper and lower precursor concentration data. Most fuel structural materials show concentrations around 1 ppm.

Although the production of tritium is somewhat different from that of C-14 (and tritium is mobile in reactor materials), a similar approach has been used for apportioning the H-3 inventory to material types.

The apportioning of H-3 activity where there is more than one activated material is determined by the following factors:

- M: the fraction of waste stream mass associated with the material
- N: the concentration (in ppm) of lithium in the material (it is assumed that the major H-3 production route is the Li-6(n,α)H-3 activation reaction)
- F: the relative thermal neutron flux to which the material has been exposed (the same values used for the C-14 calculations are adopted)

Table A-29. Average lithium concentrations in reactor materials.

Material	Lithium concentration (ppm)
Stainless steel 304	0.63
Stainless steel 20/25/Nb	0.792
Stainless steel 18/9	0.63
Mild steel	0.63
Magnox AL80	0.041
Magnox ZR55	0.063
Zircaloy	0.513
Nimonic	0.847
Uranium	5
UO_2 (AGR)	0.2
UO_2 (LWR)	1
Reactor graphite (Magnox)	0.080
Reactor graphite (AGR)	0.168
Fuel graphite	0.671
Sintox	1.583

Appendix B: Waste containers

The primary goal of the IGD is to quantify the amount of waste destined for geological disposal. The design of the disposal container for each type of waste is a key factor in deriving the total packaged volume and mass of waste destined for geological disposal. This Appendix gives details of each type of waste container in the IGD.

B.1. Low Heat Generating Waste Containers

B.1.1 ILW and LLW waste containers

NWS's illustrative geological disposal concept examples are based on three general waste container types: unshielded, shielded and robust shielded. The range of waste containers for geological disposal for which NWS has standardised designs is shown in Table B-1. Where a transport container is required, a re-usable standard waste transport container (SWTC) is used; these transport containers have either 70 mm or 285 mm of steel shielding to satisfy dose rate requirements. However, in the case of the miscellaneous beta gamma waste store (MBGWS) box and the 500 l RS drum, an SWTC with 150 mm of steel shielding will be used. 2m and 4m boxes can have a range of thicknesses of internal concrete shielding.

The properties of the full range of ILW and LLW waste containers are listed in Table B-2.

Table B-1. Standard designs of LHGW-containing waste containers covered by NWS waste package specifications [25]

Waste container	Transport container
500 l drum	SWTC with 70 mm or 285 mm of steel shielding
3m^3 drum	
3m^3 box (side lifting)	
3m^3 box (corner lifting)[28]	
MBGWS box	SWTC with 150 mm of steel shielding
500 l RS drum	
3m^3 RS box	Transport container design to be based on that of an International Organization for Standardization (ISO) freight container
2m box	Packages of waste in these shielded containers will qualify as transport packages in their own right and will be classed as Type IP-2 transport packages.
4m box	
6 m^3 box	
500 l concrete drum	
1 m^3 concrete drum	

[28] The Sellafield 3m^3 box and Enhanced Sellafield 3m^3 box are instances of the 3m^3 box (corner lifting).

Table B-2. ILW and LLW containers in the 2022 IGD and their properties.

Waste Container	Preferred Material	Payload (m^3)	Displacement Volume (m^3)	Empty Mass (t)
Unshielded ILW / LLW (UILW / ULLW)				
500 l drum [29]	316L Stainless Steel	0.47	0.571	0.13
Enhanced 500 l drum (pre-cast) [30]	316L Stainless Steel / Concrete	0.4	0.571	0.40
Enhanced 500 l drum (basket) [31]	316L Stainless Steel	0.47	0.571	0.13
$3m^3$ box (side lifting) [29]	316L Stainless Steel	2.7	3.27	0.75
$3m^3$ box (corner lifting) [29]	316L Stainless Steel	2.8	3.61	0.75
$3m^3$ drum [29]	316L Stainless Steel	2.2	2.61	0.72
MBGWS	Carbon Steel	3.5	4.7	2.0
$3m^3$ Sellafield box [32]	Duplex 1.4462 SS / Concrete	2.8	3.3	1.3
$3m^3$ Enhanced Sellafield box [33]	Duplex 1.4462 SS / Concrete	2.3	3.3	2.6
Shielded ILW / LLW (ILW / LLW)				
2m box (200 mm concrete)	316L Stainless Steel / Concrete	4.9	10.2	15.0
4m box (0 mm concrete) [34]	316L Stainless Steel	18.9	20.0	5.0
4m box (100 mm concrete) [34]	316L Stainless Steel / Concrete	14.3	20.0	17.5
4m box (200 mm concrete) [34]	316L Stainless Steel / Concrete	10.9	20.0	22.5
6 m^3 concrete box (SD) [32]	Reinforced Concrete / Carbon Steel	5.76	11.9	14.0
6 m^3 concrete box (HD) [32]	Reinforced Concrete / Carbon Steel	5.76	11.9	26.0
1 m^3 concrete drum (40 mm steel)	Reinforced Concrete / Carbon Steel	0.62	2.0	4.06
Robust shielded ILW containers				
$3m^3$ RS box	Cast Iron	2.547	5.44	18.3
500 l RS drum (0 mm Pb)	Cast Iron	0.441	1.32	5.73

[29] Payload derived assuming a 200 mm gap between the top of the waste matrix and the underside of the lid; this gap will contain capping grout and ullage.

[30] Payload defined by Magnox Ltd for B462 drums; empty mass includes 0.13 t of steel.

[31] Payload is the same as for a 500 l drum.

[32] Empty weight includes 0.7 t of steel.

[33] Empty weight includes 1.5 t of steel.

[34] Payload and displacement volumes are for 4m boxes with corrugated side panels. Payloads for 4m box (no shielding and shielded) are based on the assumptions as for the 2m box. The empty mass of the shielded variants includes 5 t of steel.

B.1.2 ILW and LLW container materials

Table B-3 presents the bulk materials in the waste containers for ILW and LLW.

Table B-3. The materials used in the unshielded and shielded ILW and LLW waste containers. Data presented include the mass (M) and thickness (T).

Waste container type	Stainless steel		Carbon steel		Concrete	
	M (t)	T (m)	M (t)	T (m)	M (t)	T (m)
Unshielded ILW/LLW (UILW/LLW)						
500 l drum	0.13	0.003				
Enhanced 500 l drum (pre-cast)	0.13	0.003			0.27	0.04
Enhanced 500 l drum (basket)	0.13	0.003				
3m^3 box (side lifting)	0.75	0.006				
3m^3 box (corner lifting)	0.75	0.006				
3m^3 drum	0.72	0.003				
MBGWS			2	0.006		
3m^3 Sellafield box	0.7	0.006			0.6	0.03
3m^3 Enhanced Sellafield box	1.5	0.006			1.1	0.05
Shielded ILW / LLW (ILW / LLW)						
2m box (0 mm concrete)	3	0.006				
2m box (100 mm concrete)	3	0.006			7	0.1
2m box (200 mm concrete)	3	0.006			12	0.2
2m box (300 mm concrete)	3	0.006			15.5	0.3
4m box (0 mm concrete)	5	0.003				
4m box (100 mm concrete)	5	0.003			12.5	0.1
4m box (200 mm concrete)	5	0.003			17.5	0.2
6 m^3 concrete box (SD)			0.7	0.003	13.3	0.24
6 m^3 concrete box (HD)			0.7	0.003	25.3	0.24
1 m^3 concrete drum (40 mm steel)			1.57	0.04	2.49	0.16
Robust shielded ILW containers						
3m^3 RS box			18.3	0.15		
500 l RS drum (0 mm Pb)			5.73	0.12		

B.1.3 DNLEU

The packaging assumptions for DNLEU that is less than 1% enriched (based on the preferred options identified by the Uranium Integrated Project Team) are that:

- 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 TDC, which is a 20-foot IP-2 rated 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 remaining DNLEU (i.e. miscellaneous DNLEU, TPU and uranium tetrafluoride) is assumed to be repackaged into 500 l drums for disposal.

The DNLEU streams suitable for disposal in TDCs will be infilled with a 3:1 mixture of blast furnace slag (BFS) or pulverised fuel ash (PFA) : Portland Cement (CEM I) grout prior to disposal. The remaining DNLEU repacked into 500 l drums is assumed to be converted into U_3O_8 powder, which would be mixed with a PFA:OPC encapsulant and repackaged into 500 l drums for disposal.

Table B-4 gives the masses of the components that make up a single DNLEU 500 l drum.

Data regarding the masses of the components that comprise the ~500 l overpack for older MDU and the grout-filled TDCs are provided in Table B-5 to Table B-7.

Table B-4. Properties of the 500 l drum for DNLEU.

Item	Mass (t)	Material composition	Notes
U_3O_8 (equivalent mass of U)	1.14 (0.967)	U_3O_8	Density of U_3O_8 is 8.3 t/m^3
Encapsulating grout	0.44	1:1 PFA / OPC	
Water (for encapsulating grout)	0.19		Assuming 29% water content of grout
Capping grout (includes water)	0.09	3:1 PFA / OPC	
Steel (lost paddle)	0.01		
Steel drum	0.13	SS 316L	
Total	2.0		500 l drum payload volume 0.47 m^3; displacement volume 0.57 m^3; and a 2 t mass limit

Table B-5. Properties of the TDC for MDU (current stocks).

Item	Mass (t)	Material composition	Notes
U_3O_8 (equivalent mass of U)	19.2 (16.0)	UO_3	Assumed UO_3 powder density of 4.9 t/m^3
200 l drums	0.56	Mild steel	28 × 200 l drums per TDC
Polythene bags (200 l drums)	0.007	LDPE	
500 l overpack	1.96	Stainless steel	28 × 500 l drums per TDC
Polythene bags (500 l overpack)	0.038	HDPE	
Encapsulating grout	9.59	3:1 BFS/PFA: OPC	
Water (for encapsulating grout)	3.92		Assuming 29% water content of grout
TDC	6.5		
Total	41.8		Payload volume 21.92 m^3; displacement volume 29.08 m^3

Table B-6. Properties of the TDC for MDU (future arisings).

Item	Mass (t)	Material composition	Notes
U_3O_8 (equivalent mass of U)	38.9 (32.4)	UO_3	Assumed UO_3 powder density of 4.9 t/m^3
210 l drums	1.296	Stainless steel	54 × 210 l drums per TDC
Polythene bags (210 l drums)	0.014	LDPE	
Encapsulating grout	5.87	3:1 BFS/PFA: OPC	
Water (for encapsulating grout)	2.4		Assuming 29% water content of grout
TDC	6.5		
Total	54.9		Payload volume 18.79 m^3; displacement volume 25.44 m^3

Table B-7. Properties of the TDC for depleted uranium tails.

Item	Mass (t)	Material composition	Notes
U_3O_8 (equivalent mass of U)	41.0 (34.8)	U_3O_8	Density of U_3O_8 powder is 4.0 t/m^3
DV-70 containers	3	Mild steel	4 DV-70s per TDC
Encapsulating grout	5.60	3:1 BFS/PFA: OPC	
Water (for encapsulating grout)	2.29		Assuming 29% water content of grout.
TDC	6.5		
Total	58.4		Payload volume 19.84 m^3; displacement volume 27.87 m^3

B.1.4 Verification of ILW and LLW waste and transport container allocations

Legacy and new build ILW and LLW stream container allocations are entered into the IGD dataset in NWS's inventory database software, which is then used to generate package dose rates, heat outputs, A_2 multiples, and the fissile status of packages. These are then compared with numerical limits given in specifications and regulations.

It is assumed that all waste streams packaged in unshielded containers (e.g. 500 l drums, 3 m^3 boxes, 3 m^3 drums) will be transported to the GDF in SWTCs. This transport container will have 70 mm, 150 mm (MBGWS boxes and 500 l RS drums only) or 285 mm of steel shielding in order to meet limits on dose rates. The inventory database software automatically assigns the appropriate transport container (to meet International Atomic Energy Agency (IAEA) regulations) for a waste stream packaged in an unshielded waste container.

The waste and transport container numerical limits that are checked are shown in Table B-8. If these limits are exceeded by greater than 25% of the expected date of transport then the waste container allocations are revised. For shielded containers an extra 100 mm of concrete shielding is taken to reduce dose rates by a factor of 1.5 (a conservative assumption based on the high energy gamma emissions from Co-60). Waste streams in a 2m box or 4m box where 200 mm of concrete shielding is insufficient are reallocated to a 3 m^3 box (side lifting). Where waste streams in unshielded containers exceed dose rate limits for a transport container with 285 mm of steel shielding, the waste loading volume in the container is reduced so that dose rates are below the limits.

Table B-8. Waste package numerical limits applied in package analysis.

Container type	Dose rate limit (mSv/hr)			Heat output limit per transport package (watts)	Ref
	On surface	At 1m	At 3m		
500 l drum	2	0.1		100 per drum	[26]
500 l drum (basket)					
500 l drum (pre-cast annular)					
3m³ drum	2	0.1		400	[26]
3m³ box (side lifting)					
3m³ box (corner lifting)					
Sellafield 3m³ box					
Sellafield enhanced 3m³ box					
MBGWS box					
500 l RS drum					
$3m^3$ RS box	2	0.1			[26]
2m box	2	0.1	10	60	[26]
4m box	2	0.1	10	200	[26]
$6m^3$ box	2	0.1	10	60	[26] & [27]
500 l concrete drum	2	0.1			[26]
1 m^3 concrete drum					

B.2. High Heat Generating Waste Containers

B.2.1 Containers for SF, HLW, plutonium and highly enriched uranium

NWS's development of HHGW disposal containers has been based on the assumed requirements for disposal in accordance with the adoption of each of the three illustrative disposal concepts (for potential types of host rock) [28]. This has resulted in two basic design variants:

- Variant 1: Fabricated from copper, with a cast iron insert (i.e. based on the KBS-3 container concept designed by the Swedish radioactive waste management organisation SKB [29]), for compatibility with the needs of a GDF constructed in a HSR; and
- Variant 2: Fabricated from carbon steel (i.e. based on the container designed by the Swiss radioactive waste management organisation NAGRA [30]), for compatibility with the needs of a GDF constructed in LSSR or EVR.

The choice of variant used for disposal of HHGW in a GDF will depend on the host rock in which the GDF is constructed. For the purposes of quantifying a single inventory for disposal, it is assumed that the Variant 2 disposal container is used. Since the variant packages have very similar dimensions, the only IGD parameters that vary significantly, depending on the container choice, are the material masses and elemental compositions.

HLW is conditioned by immobilising it in glass (vitrification) in stainless steel WVP canisters. Three WVP canisters are assumed to be packaged into a single disposal container, while four spent PWR fuel assemblies are assumed to be disposed of, intact, 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. *Figure B-**1*** shows the disposal containers for HLW, AGR SF and PWR SF.

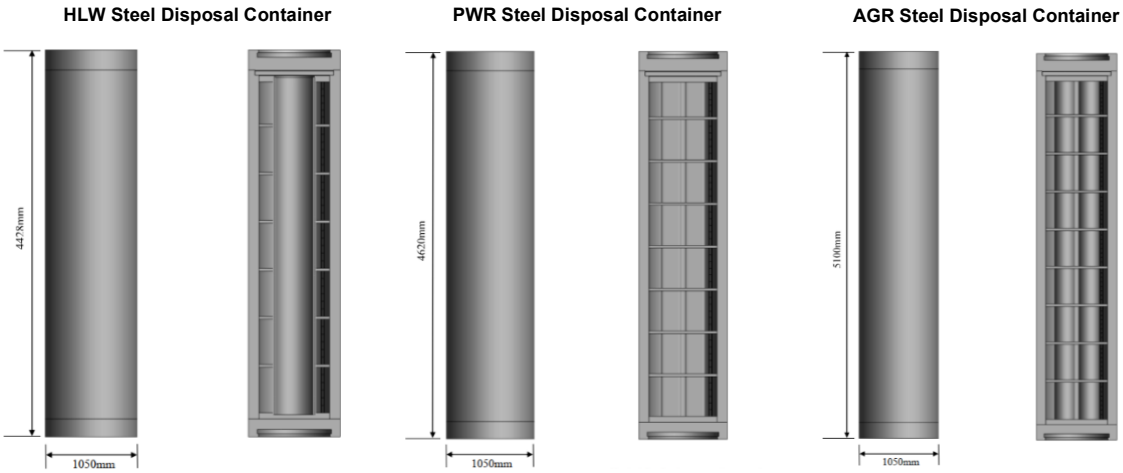

Figure B-1 Drawings of the disposal containers for HLW, Legacy PWR SF and AGR SF.

It is assumed that other SF would also be disposed of in similar disposal containers. The new build programme is assumed to consist of UK EPR and, as yet, unspecified designs for SMRs / AMRs. It is assumed that a single disposal container design will be used for these types of SF assemblies based upon the UK EPR fuel assemblies. Thermal constraints, combined with the (assumed) high burn-up of 65 GWd/tU of these fuels mean that three rather than four SF assemblies will be disposed of in a single disposal container. If the SF assemblies had a lower burn-up then it may be possible to dispose of four in a single disposal container. Illustrations for both are presented in Figure B-2.

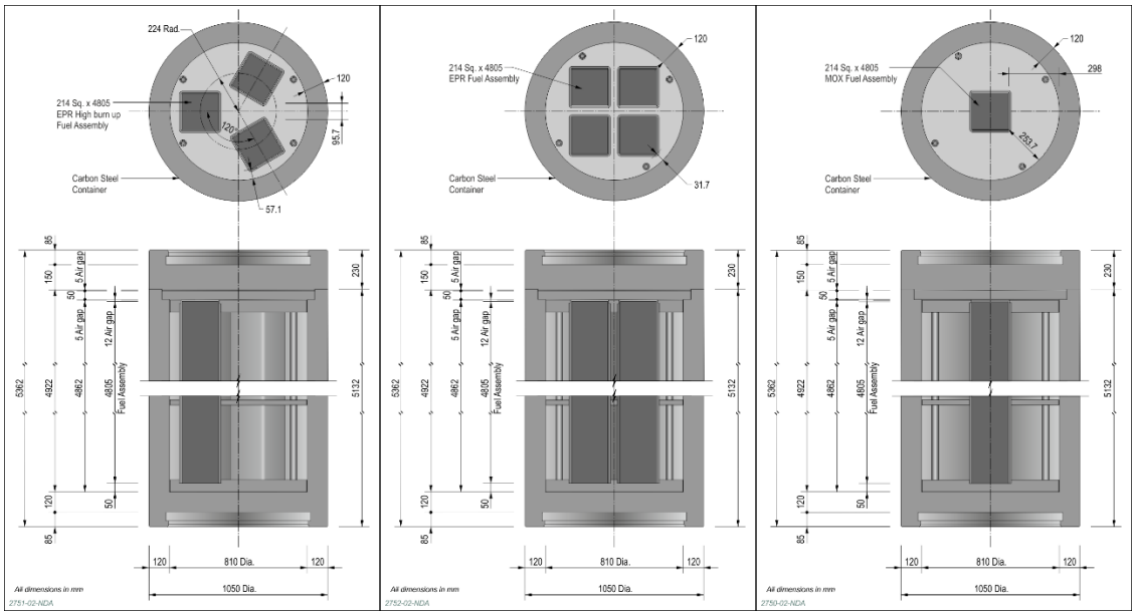

Figure B-2 Disposal containers for the new build and MOX SF.

MOX fuel assemblies are assumed to have similar dimensions to the UK EPR fuel assemblies. As a result of thermal constraints and the high thermal output of a spent MOX fuel assembly, it is currently assumed that there is only a single assembly in a disposal container (shown in Figure B-2).

Although the Sellafield legacy ponds (metallic) fuels are likely to comprise various fuel types from several sources, the majority are likely to be Magnox reactor fuel. It is assumed that 26 Magnox fuel elements will be packaged inside a fuel canister, and that three fuel canisters are stacked in a single disposal container, as shown in *Figure B-**3***. It is assumed that seven exotic (PFR) SF assemblies are disposed of in a single disposal container, as shown in *Figure B-**3***.

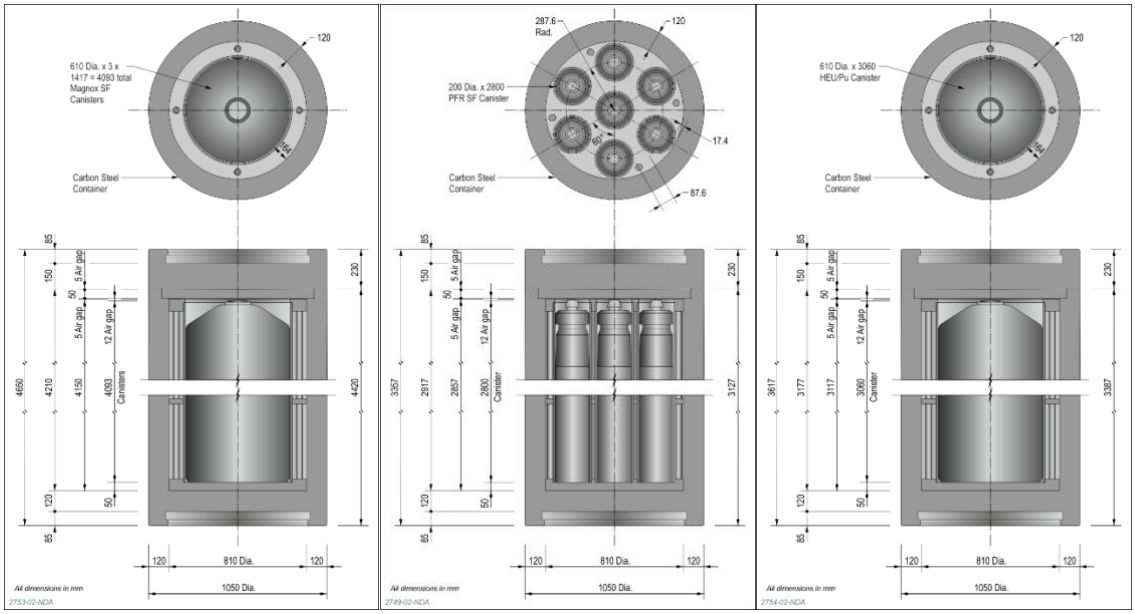

Figure B-3 Disposal containers for metallic (Magnox legacy ponds) fuels, PFR SF and Pu / HEU.

The can-in-canister concept (see Appendix C.2) is assumed for HEU and residual plutonium (plutonium which is not suitable for fabrication into MOX). 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 the disposal container, as shown in *Figure B-**3***.

The packaging assumptions for SF, HLW and Pu / HEU have not been optimised and do not foreclose other options. As a result, the packaging assumptions are subject to change.

B.2.2 Package material data

The materials used in the disposal containers are shown in Table B-9 along with the payload volumes and the packaged volumes of the disposal containers. The data for the HLW, AGR SF and PWR SF disposal containers are based on technical drawings, while the data for the other disposal containers are based on the illustrative drawings shown in Figure B-2 and *Figure B-**3***. The material masses have been calculated for the disposal containers assuming the density of carbon steel to be 7.85 t/m^3.

Table B-9. The materials used in the disposal containers.

Disposal container	Payload [m^3]	Package volume [m^3][35]	Carbon steel mass [t]	Total mass [t]
HLW	0.583	3.74	14.9	14.9
AGR SF	0.885	4.30	17.6	17.6
PWR SF	0.744	3.91	16.2	16.2
Magnox SF	1.20	3.93	15.4	15.4
PFR SF	0.597	2.81	12.2	12.2
MOX SF	0.220	4.55	17.9	17.9
3 assembly new build SF	0.659	4.55	18.3	18.3
4 assembly new build SF	0.878	4.55	18.4	18.4
HEU / Pu	0.890	3.04	12.31	12.3

[35] The packaged volumes presented in this table are displacement volumes (which take account of the handling features) and not envelope volumes.

Appendix C: Conditioning and capping materials

There are no conditioning or capping materials associated with legacy SF, MOX SF, new build SF, HLW, or with RSCs.

The methodology for assigning the conditioning and capping materials for the remaining wastes is described in the sections below.

C.1. ILW and LLW

C.1.1 ILW and LLW conditioning materials

Many waste streams are assumed to be encapsulated by a conditioning matrix to ensure a monolithic wasteform for transport and ultimate disposal. Conditioning the waste also ensures that voidage in the package is eliminated to mitigate possible package failure for stacked packages in ILW vaults of the GDF and to reduce potential post-closure flow paths for groundwater. For new build ILW streams, the choice of conditioning matrix has been based on the UK Inventory operational ILW streams at Hinkley Point C and from GDA submissions for decommissioning wastes[36].

Where ILW and LLW waste streams are reported to be packaged with a conditioning matrix, but that conditioning matrix is not defined or quantified, enhancements are carried out to produce a quantified inventory for the conditioning materials. The methodology for enhancing an unquantified conditioning matrix for waste streams in the UK Inventory is detailed below:

1. For waste streams that are reported to be encapsulated directly in a cementitious matrix, calculate the volume of conditioning grout. This is the reported container payload volume minus the waste loading per package (Note: any capping grout is not part of the reported container payload volume).
2. For waste streams that undergo a pre-treatment volume change or have no estimate of waste loading, the volume of grout is based on a surrogate stream. Surrogate streams are selected as a ‘best match’ (i.e., those with the same, or very similar characteristics).
3. Convert volume of conditioning grout to mass using a grout density of 1.8 t/m^3. (If a non-typical grout composition is reported an alternative density is used).
4. Use cement constituents (i.e., OPC, BFS / PFA) as reported in the UK Inventory. Where no information is given, assume the following:
    - 3:1 BFS:OPC for solid wastes
    - 9:1 BFS:OPC for ion exchange materials, sludges and liquids

[36] All new build ILW streams are assumed to be encapsulated in cementitious grout with the same 3:1 BFS:OPC ratio, water content and elemental composition as that for other ILW. The exception to this is Ion Exchange Resin streams, which are assumed to be encapsulated in a polymer conditioning matrix.

5. For the grout make-up, assume a typical water / cement (w / c) ratio of 0.4 by volume or 0.29 by mass.
6. Grout loadings for overpacked waste streams are calculated individually with 4 m boxes used to overpack type 1803 drums and 3 m^3 boxes to overpack non-standard drums.
7. For wastes conditioned in a polymer matrix encapsulant, loadings are calculated in the same way as for grout loadings and the relevant polymer density is used to calculate the mass.
8. Uncertainties in masses of conditioning materials are determined using the waste stream volume uncertainty factors reported in the UK Inventory.
9. Waste streams packaged in 500 l RS drums and 3 m^3 RS boxes have no conditioning matrix.

C.1.2 ILW and LLW capping materials

Capping grout is required in some waste packages as an additional protective layer. This is the case where there is a risk that loose, mobile radioactive material may be present at the top of an otherwise immobilised wasteform, rendering it readily dispersible under accident conditions (e.g. for sludge wastes).

Capping grout is not reported for waste streams in the UK Inventory and therefore the data are included through enhancements. The steps used to enhance the data for capping materials are:

1. Assign the volume and mass of capping grout to each waste stream according to the container type allocation.
2. Determine the elemental composition by assigning the component make-up of OPC and PFA (see Table C-1).

The volume and mass of capping grout for each container are given in Table C-2. All capping grout is assumed to comprise OPC, PFA and water in the ratio 1 : 3 : 0.7, with the exception of 2 m and 4 m boxes, where the capping grout is iron-shot concrete (comprising 75% iron and 25% concrete by mass).

Table C-1. Composition of materials used in waste conditioning grout.

Species	Typical composition [% by mass]		
	OPC	PFA	BFS
CaO	64.1	41.4	1.7
SiO_2	21.0	32.9	51.0
Al_2O_3	5.1	13.5	25.6
Fe_2O_3	3.1	0.8	9.6
MgO	2.5	8.3	1.6
SO_3	2.2	-	0.7
K_2O	0.7	0.4	3.8
Na_2O	0.3	0.2	-
C	-	-	2.8
Chloride	0.03	0.03	-
Sulphide	-	0.9	-
Free lime	0.8	-	-
Insolubles	0.3	-	-

Table C-2. Volumes and masses of capping grout for LLW and ILW waste containers in the 2022 IGD.

Waste container type	Capping grout		
	Volume [m^3]	Mass [t]	Type
UILW / ULLW			
500 l drum	$3.5\ 10^{-2}$	0.06	Cement grout
Enhanced 500 l drum (pre-cast)	$3.5\ 10^{-2}$	0.06	Cement grout
Enhanced 500 l drum (basket)	$3.5\ 10^{-2}$	0.06	Cement grout
3 m^3 box (side lifting)	$2.0\ 10^{-1}$	0.33	Cement grout
3 m^3 box (corner lifting)	$2.0\ 10^{-1}$	0.33	Cement grout
3 m^3 drum	$1.83\ 10^{-1}$	0.3	Cement grout
MBGWS box	$2.0\ 10^{-1}$	0.33	Cement grout
3 m^3 Sellafield box	$2.0\ 10^{-1}$	0.33	Cement grout
3 m^3 Enhanced Sellafield box	$2.0\ 10^{-1}$	0.33	Cement grout
SILW / SLLW			
2 m box (200 mm concrete)	$5.5\ 10^{-1}$	3.19	Iron-shot concrete
4 m box (no shielding)	$8.97\ 10^{-1}$	5.2	Iron-shot concrete
4 m box (100 mm concrete)	$7.77\ 10^{-1}$	4.51	Iron-shot concrete
4 m box (200 mm concrete)	1.33	7.71	Iron-shot concrete

C.2. HEU and Plutonium conditioning materials

Several assumptions have had to be made regarding the disposal concept for Pu / HEU. The can-in-canister concept has been assumed, but the packaging and conditioning assumptions for Pu / HEU have not been optimised and do not foreclose other options. As a result, the packaging assumptions are subject to change.

The can-in-canister approach has been developed in the USA for the packaging of plutonium in ceramic together with HLW in glass. It is assumed that for the packaging of UK plutonium and HEU the HLW glass is replaced with inactive borosilicate glass. A nominal 10 wt% of plutonium (~50 g) is immobilised in a titanate-based ceramic to form a puck, with a 6.9 cm diameter and 2.5 cm thickness. The composition of the ceramic is given in Table C-3.

Twenty pucks are assumed to be loaded into a stainless steel can that is 7.6 cm in diameter and 51 cm in length; 28 of these cans are assumed to be encapsulated in glass within a large canister. The large canister is a steel cylinder 61 cm in diameter and 3.06 m in height (external volume 0.89 m^3).

There is no further information on the packaging approach in the reference material. Therefore, several assumptions have been made for material characteristics and in the calculation of materials masses (see Table C-3). The dimensions of the steel canister are such that a single canister would be loaded in a mild steel disposal canister. There is no design information for such a mild steel disposal canister, hence several assumptions have been made to derive nominal volumes and masses for materials. Table C-4 gives the results of calculations for a single mild steel disposal canister.

Table C-3. Composition of the titanate-based ceramic.

Oxide	Composition [% by mass]
PuO_2 (or HEU dioxide)	11.9
UO_2	23.7
HfO_2	10.6
Gd_2O_3	7.9
CaO	10.0
TiO_2	35.9

Table C-4. Assumptions used in the derivation of masses of waste and packaging materials for the Pu / HEU disposal container.

Item	Assumptions	Mass [t]
Ceramic pucks	69 mm diameter; 25 mm thickness Mass 500 g; volume 93.5 cm^3 20 pucks per can; 28 cans per canister	0.280, of which UO_2 / PuO_2 3.33 10^{-2} implying U / Pu 2.94 10^{-2}
Stainless steel cans	Length 510 mm; 76 mm outer diameter; wall thickness 3 mm; end thickness 5 mm Made of SS316; density 7.8 t/m^3 Assumed to be supported by internal canister furniture	0.085
Steel canister	Length 3060 mm; 610 mm outer diameter; external volume 0.89 m^3; wall thickness 50 mm Made of SS316; density 7.8 t/m^3	2.26
Glass encapsulant	Borosilicate glass; density 2.5 t/m^3; volume 0.525 m^3	1.31

Appendix D: Construction and operating materials

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 (e.g. 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 NWS's GDF 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 NWS'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'

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