Radioactive Waste Management

DSSC/405/01

Inventory for geological disposal

Method Report

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RWM Feedback
Radioactive Waste Management Limited
Building 587
Curie Avenue
Harwell Campus
Didcot
OX11 0RH
UK

email: rwmdfeedback@nda.gov.uk

Preface

Radioactive Waste Management Limited (RWM) has been established as the delivery organisation responsible for the implementation of a safe, sustainable and publicly acceptable programme for the geological disposal of the higher activity radioactive wastes in the UK. As a pioneer of nuclear technology, the UK has accumulated a legacy of higher activity wastes and material from electricity generation, defence activities and other industrial, medical and research activities. Most of this radioactive waste has already arisen and is being stored on an interim basis at nuclear sites across the UK. More will arise in the future from the continued operation and decommissioning of existing facilities and the operation and subsequent decommissioning of future nuclear power stations.

Geological disposal is the UK Governments' policy for higher activity radioactive wastes. The principle of geological disposal is to isolate these wastes deep underground inside a suitable rock formation, to ensure that no harmful quantities of radioactivity will reach the surface environment. To achieve this, the wastes will be placed in an engineered underground facility – a geological disposal facility (GDF). The facility design will be based on a multi-barrier concept where natural and man-made barriers work together to isolate and contain the radioactive wastes.

To identify potentially suitable sites where a GDF could be located, the Government has developed a consent-based approach based on working with interested communities that are willing to participate in the siting process. The siting process is on-going and no site has yet been identified for a GDF.

Prior to site identification, RWM is undertaking preparatory studies which consider a number of generic geological host environments and a range of illustrative disposal concepts. As part of this work, RWM maintains a generic Disposal System Safety Case (DSSC). The generic DSSC is an integrated suite of documents which together give confidence that geological disposal can be implemented safely in the UK.

Executive Summary

The UK has been producing radioactive waste inventories for over 30 years and this is now a well-established iterative process. The UK Government's 2014 'Implementing Geological Disposal White Paper' defines the inventory for disposal in a geological disposal facility in terms of types of higher activity radioactive wastes (and nuclear material that could be declared as waste). In order to support the implementation of geological disposal RWM has developed a quantified description of this inventory called the 'Inventory for geological disposal' (IGD).

This report presents the method for compiling the IGD and was produced alongside the 2016 IGD. The key points are that:

- the IGD is based on a 'scenario', which describes how waste and nuclear materials will arise and be managed
- the IGD is based on publicly available information, principally the UK Radioactive Waste and Materials Inventory (RWI)
- the IGD takes account of Government policy and industry plans
- RWM have supplemented the data in some areas (eg where data is not provided in the UK RWI), and details of this are presented in this report

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Introduction

1.1 The generic Disposal System Safety Case

RWM has been established as the delivery organisation responsible for the implementation of a safe, sustainable and publicly acceptable programme for geological disposal of the UK's higher activity radioactive waste. Information o n the approach of the UK Government and devolved administrations of Wales and Northern Ireland[1] to implementing geological disposal, and RWM's role in the process, is included in an overview of the generic Disposal System Safety Case (the Overview) [1].

A geological disposal facility (GDF) will be a highly-engineered facility, located deep underground, where the waste will be isolated within a multi-barrier system of engineered and natural barriers designed to prevent the release of harmful quantities of radioactivity and non-radioactive contaminants to the surface environment. To identify potentially suitable sites where a GDF could be located, the Government is developing a voluntarism approach based on working with interested communities that are willing to participate in the siting process [2]. Development of the siting process is ongoing and no site has yet been identified for a GDF.

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

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

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

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

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

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

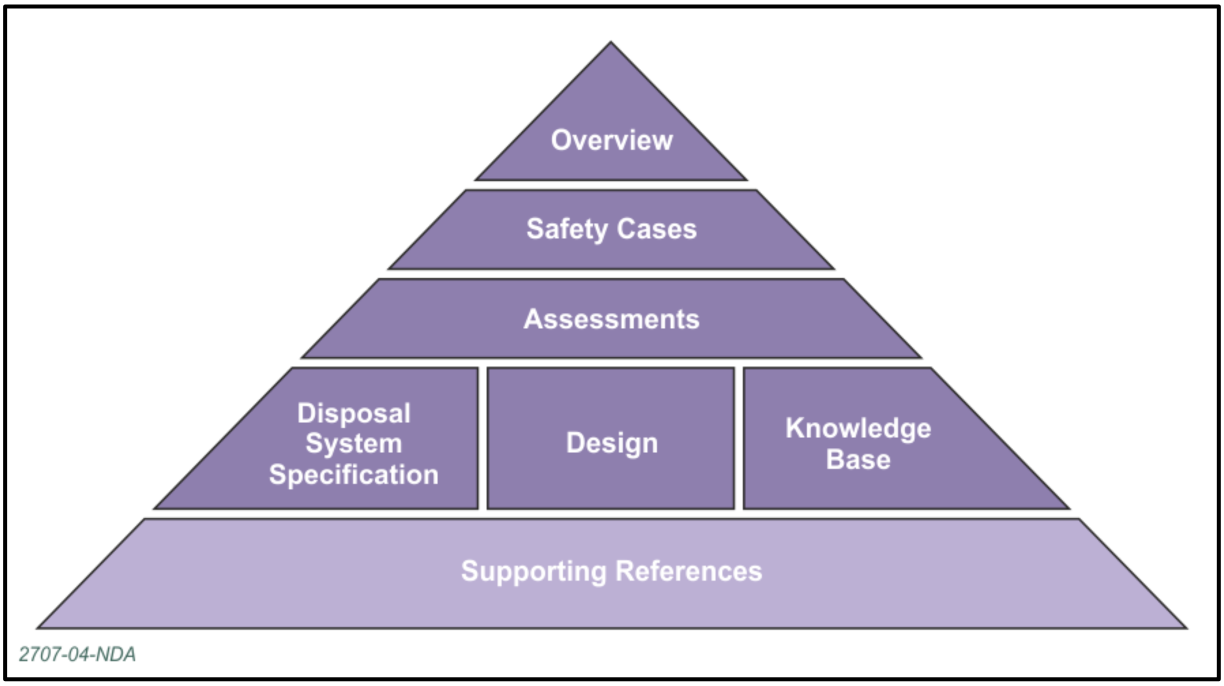
High level information on the inventory for disposal, the illustrative disposal concepts and other aspects of the disposal system is collated in a technical background document (the Technical Background) [3] that supports this generic Disposal System Safety Case.

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

The generic DSSC provides a demonstration that geological disposal can be implemented safely. The generic DSSC also forms a benchmark against which RWM provides advice to waste producers on the packaging of wastes for disposal.

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

Figure 1 Structure of the generic DSSC



1.2 Introduction to the 'method report'

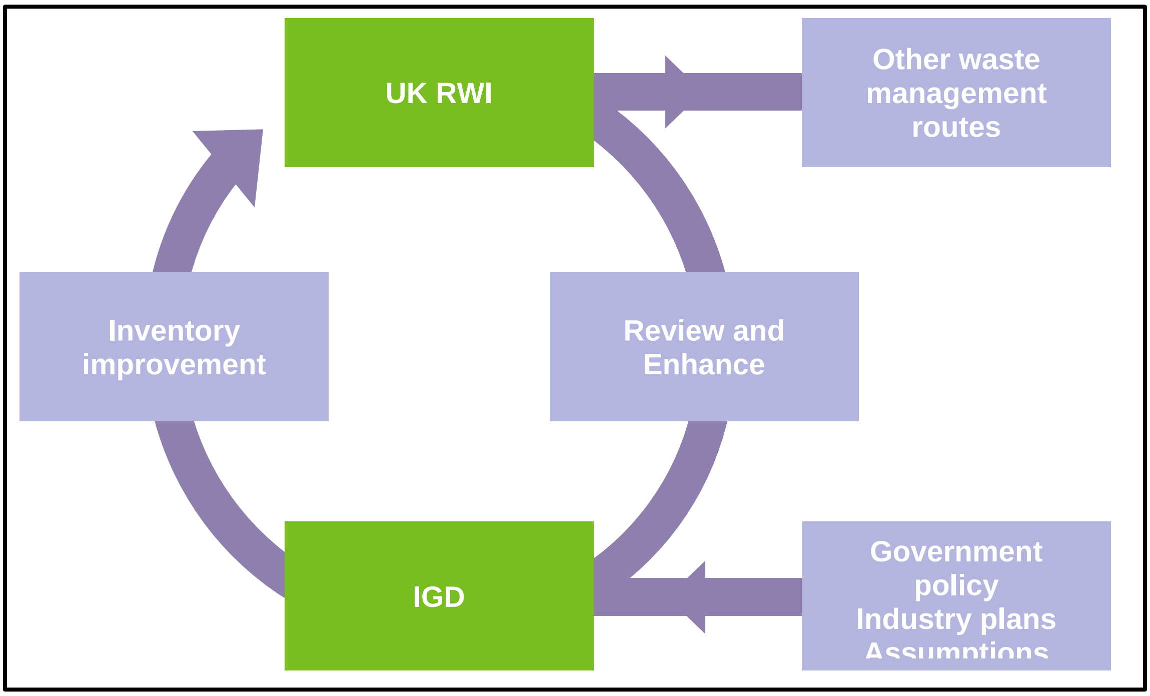
This document is the '2016 inventory for geological disposal: method report'. It is one of five reports that deal with various aspects of the 2016 inventory for geological disposal (IGD). The other four reports are:

- the 'Main report' [4], which describes the principal features of the 2016 IGD
- the 'Differences report' [5] which sets out the differences between the 2016 IGD and the previous version (the 2013 IGD [6][2])
- the 'Implications report' [7], which describes the implications of the 2016 IGD for the generic DSSC
- the 'Alternative scenarios report' [8], which provides information on how changes to the scenario for future waste arisings would affect the 2013 IGD, and which is updated in the Differences report [5].

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

Currently, the UK RWI is updated every three years, after which the IGD is updated, as shown in Figure 2.

Figure 2 The iterative development of the Inventory for geological disposal



The most recent version of the UK RWI [9] is based on a stock date of 1st April 2016 and is referred to here as the 2016 UK RWI. The generic DSSC was published in 2017 and was based on the 2013 IGD [6], which in turn was based on the previous 2013 UK RWI [10]. The 2016 IGD is based on the 2016 UK RWI.

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2 Originally published as the 2013 Derived Inventory; it is referred to here as the 2013 IGD.

This report describes the general method for the production of an IGD, and gives specifics for the 2016 IGD. It is new to the generic DSSC suite of documents.

1.3 Objective

The objective of the 'method report' is to explain how an IGD is compiled. The method is reasonably mature with little change in the approach since 2003 when the first 'Derived Inventory' was produced based on the 2001 UK RWI [11].

The method report provides the information necessary to reproduce an IGD; it also provides specific information relating to the 2016 IGD.

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

1.4 Scope

Certain areas of the IGD scope have established methodologies that are not expected to change, other areas of the IGD scope have methods that could continually be improved or may change with evolving data requirements. These areas are reported below.

The areas of scope that are mature and where the method of production is not expected to change significantly are:

- Basis
- Scenarios
- Data requirements

The areas of the IGD scope where the method has significantly evolved over time and may continue to change are:

- Review and enhancement of data
- Reporting

1.5 Report Structure

The main body of the report provides a description of the process for producing the IGD, which is intended to be used as a manual for inventory production.

The appendices are intended to be used by anyone wishing to understand the limitations of the inventory: the detailed assumptions used to produce each data aspect of the IGD are reported here.

2 Basis

The basis of the IGD defines what the inventory needs to contain and why it needs to contain it. A review of current UK Government policy and the devolved national policies of Scotland and Wales provides the basis for management of higher activity radioactive waste in the UK.

UK Government policy as reported in the 2014 Implementing Geological Disposal White Paper [2] defines the inventory for geological disposal in terms of waste and material types as follows:

> *2.17. 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 reprocessing of spent nuclear fuel at Sellafield;*
> - *ILW arising from existing nuclear licensed sites, and defence, medical, industrial and educational activities;*
> - *The small proportion of LLW that is not suitable for disposal in the national Low Level Waste Repository;*
> - *Spent fuel from existing commercial reactors (yet to be declared waste) and research reactors that is not reprocessed;*
> - *Spent fuel (yet to be declared waste) and ILW from a new build programme up to a defined amount (see paragraphs 7.39 – 7.41);*
> - *Plutonium stocks – residual plutonium not re-used in new fuel manufacture (yet to be declared waste);*
> - *Uranium stocks – including that arising from enrichment and fuel fabrication activities (yet to be declared waste);*
> - *Irradiated fuel and nuclear materials (yet to be declared waste) from the UK defence programme.*

The Welsh Government has also adopted a policy for disposal of higher activity radioactive waste to a GDF based on a voluntary partnership with interested local communities [12].

There are no nuclear licensed sites or higher activity waste in Northern Ireland, the Northern Ireland Executive does not have a separate policy for managing higher activity waste and Northern Ireland continues to support the implementation of geological disposal for the UK's higher activity radioactive waste,

The Scottish government has not adopted a policy of geological disposal for Scottish higher activity waste. The Scottish Government's policy for HAW arising in Scotland is to be managed in near-surface facilities[3] [13]. Waste that is covered by the Scottish Government's policy[4] is therefore excluded from the inventory for geological disposal.

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3 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 [13].

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

It is not anticipated that the categories of waste and material listed above will change significantly. The volumes of these wastes and materials are regularly assessed, revised and made publicly available as part of the UK RWI. Volumes are subject to change due to a number of factors, including improvements to the estimates of waste that will arise from planned operations and decommissioning programmes.

The result of applying the basis is a defined set of waste types to be included in the IGD.

3 Scenarios

In the context of the IGD, a ‘scenario’ is the description of how the waste and nuclear materials will arise and be managed. In order to define a scenario, the following needs to be considered:

- national government policy documents on the management of nuclear materials and higher activity waste
- latest UK RWI scenario and dataset
- the management of ‘boundary wastes’, such as:
  - the small proportion of LLW that is not suitable for disposal to the LLWR
  - whether or not ILW streams expected to be managed as LLW have an approved disposal route
- defence policy documents for inventory of defence materials and higher activity waste
- industry plans, such as:
  - innovative waste packaging assumptions
  - new nuclear power stations
  - other new higher active waste producing facilities (such as research reactors, enrichment plants etc.)
  - changes in lifetime assumptions of existing sites

3.1.1 IGD Scenario

The “IGD Scenario” is derived from the application of RWM’s best understanding of waste producer’s plans at the time of compilation. The IGD is sometimes referred to as the “Baseline Scenario”.

3.1.2 Alternative Scenarios

To explore the impact on the IGD of changes in assumptions and uncertainties in data, RWM defines a number of 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 RWM’s designs and safety cases. The current alternative scenarios cover topics such as [8]:

- changes in the quantities of Magnox and AGR fuel that are reprocessed
- the size and composition of the new build programme
- the use of UK RWI lower and upper uncertainty factors
- changes in the quantities of DNLEU for disposal.

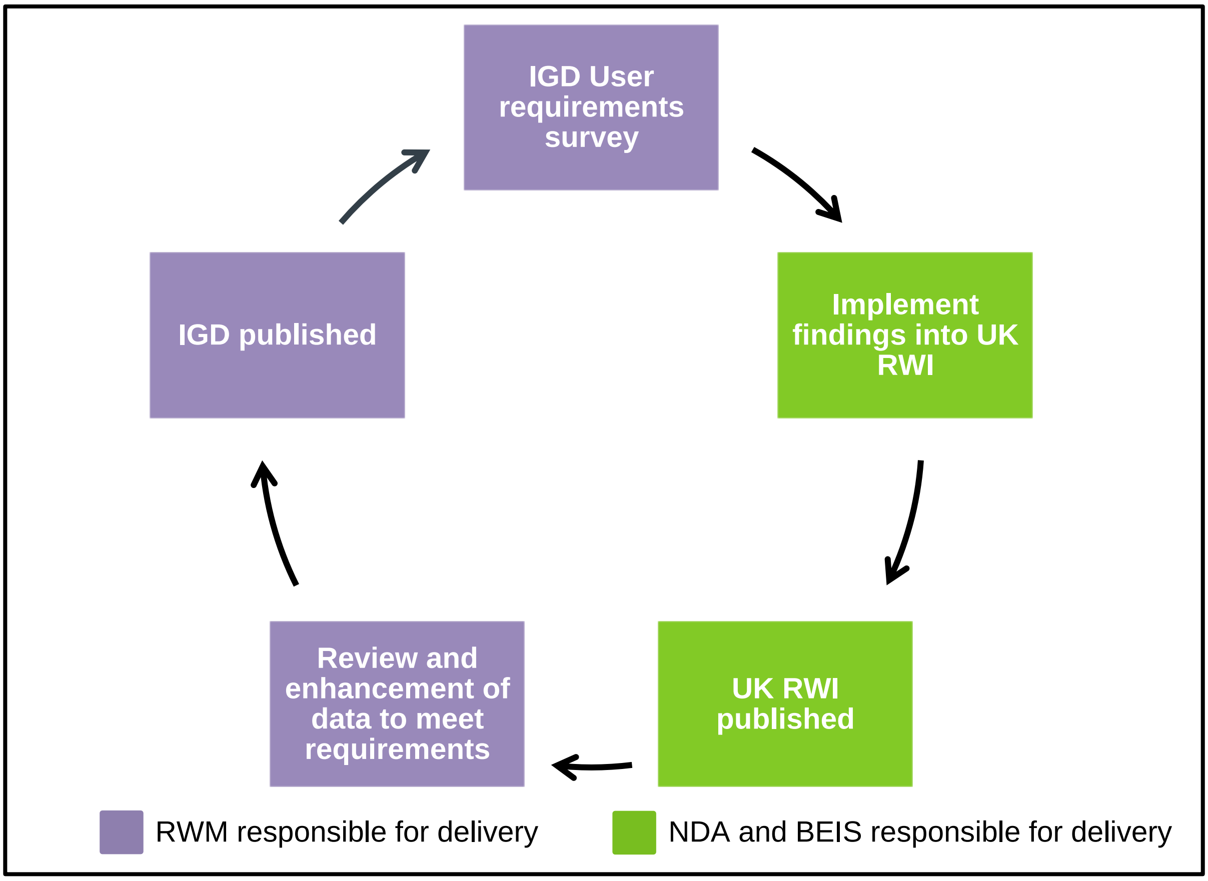
The current alternative scenarios were derived and their impacts investigated for the 2013 IGD [6]. The changes and their impacts are reported in the 2016 IGD Differences report [5].

4 Data requirements

RWM uses the IGD as the basis for its generic designs and generic safety and environmental assessments. The inventory data that are required to support this work can evolve over time (eg to meet regulatory requirements). The IGD is a sub-set of the UK RWI so new IGD data requirements are first incorporated into the UK RWI which then feed in to the IGD. Preparation of the IGD is the responsibility of RWM whereas preparation of the UK RWI is the joint responsibility of BEIS and the NDA. The following steps (see Figure 3) are carried out in order to ensure that the IGD continues to provide the required data:

- key users for the inventory for geological disposal within RWM are surveyed for their user requirements. The output from the survey informs:
  - whether the existing data fields remain relevant
  - whether any additional data fields need to be included
  - whether the priority scores[5] assigned to existing fields remain appropriate
- incorporate new data requirements into the UK RWI following discussions with NDA and data providers
- the focus of the data enhancements in the IGD are tailored to meet the data requirements
- if data requirements are not met, the findings are fed back into the next UK RWI for continuous improvement

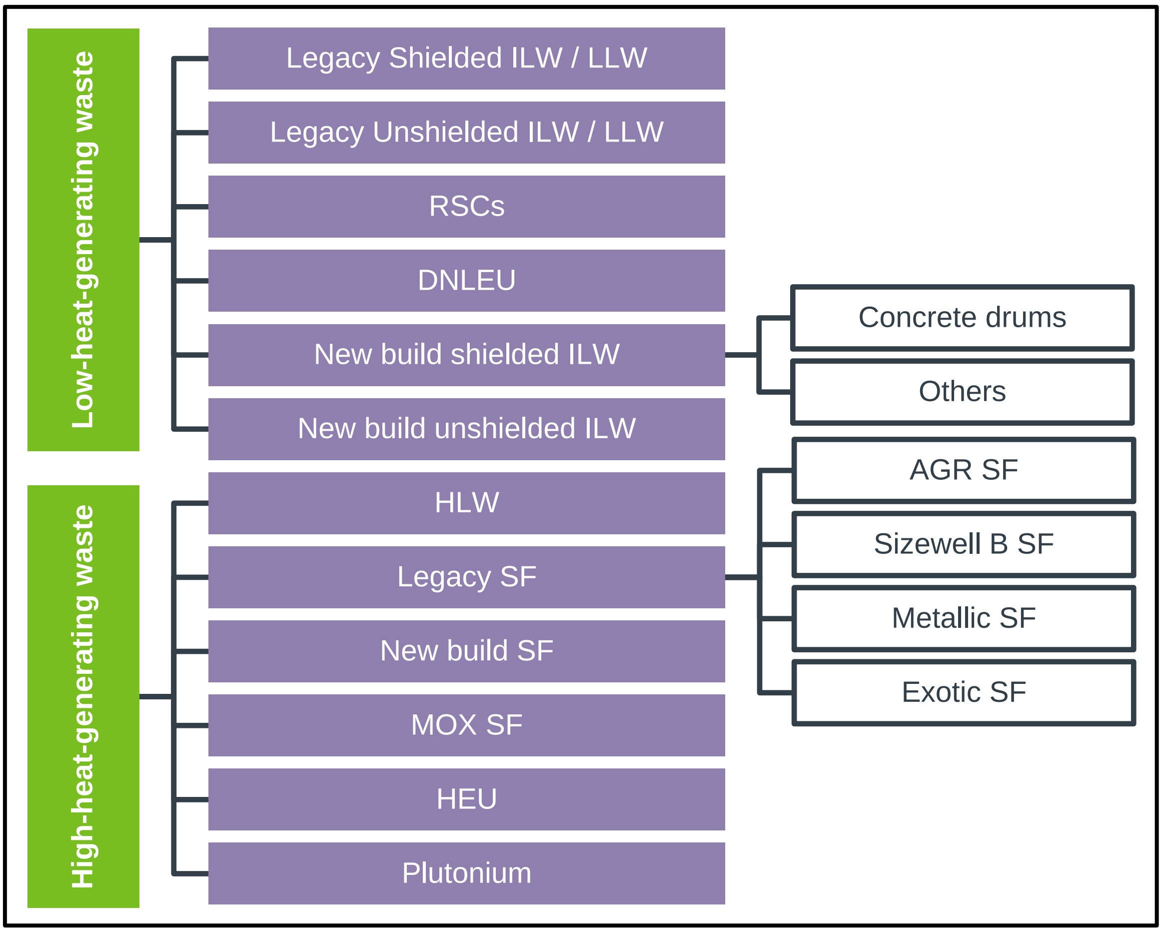
Figure 3 Process for meeting the data requirements of the IGD



[5] A measure of the importance of the data field to users of the IGD

Inventory data are reported by waste group. The waste groups have been defined by RWM to distinguish between different types of waste for RWM's design and assessment studies and to reflect the key differences in time of arising, waste packaging and assumed emplacement in the GDF. The waste groups are reviewed with changes to the origin and packaging of waste to best categorise the IGD. The IGD waste groups are listed in Figure 4.

Figure 4 The two high-level partitions of the IGD (green boxes), the waste groups (purple boxes) and the sub-groups (white boxes)



5 Review and enhancement of data

The UK RWI does not contain information on the quantities and characteristics of the components of the inventory in sufficient detail for use in RWM's design and safety and environmental assessment work.

Production of the IGD involves reviewing and enhancing the UK RWI 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 RWI 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 RWI
- potential improvements identified in UK RWI data through the review and enhancement process are prioritised and fed back into the next UK RWI

The review and enhancement method is different for 'full' and 'light' updates to the IGD. 'Full' updates include a rigorous interrogation of the entire UK RWI 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 is described below.

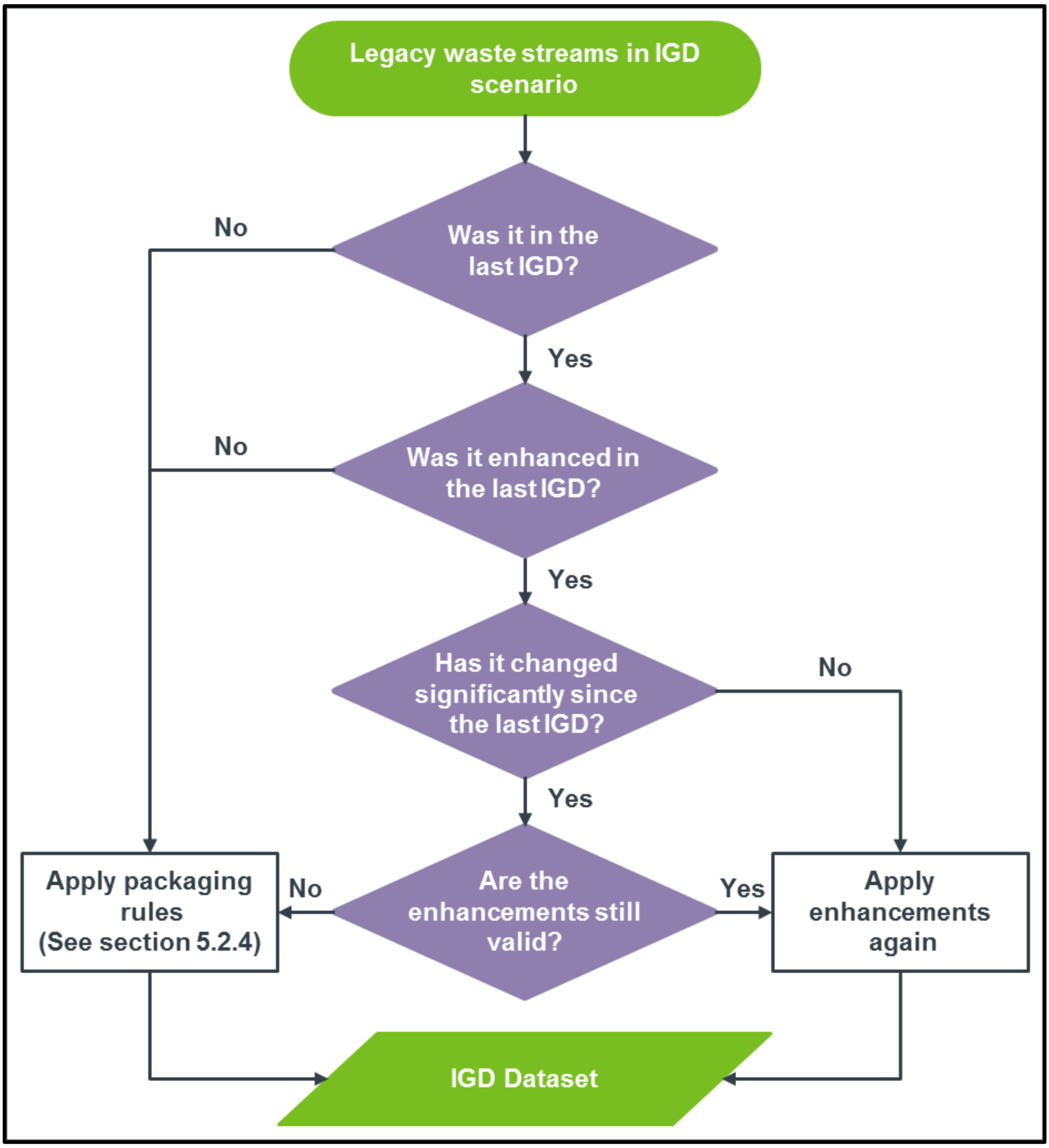
5.1 Review and enhancement for a 'light' update

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 2016 IGD can be found in section 5.2.4.

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 valid package type.
- 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 disposability assessments for Generic Design Assessments (GDAs) of new reactors and enhanced where data are missing
- for a 'light' update neither the elemental composition nor gas generation data are re-evaluated

Figure 5 the process for enhancing legacy streams in the IGD



5.2 Review and enhancement for a 'full' update

The following sub-sections provide a summary of the review and enhancement process, the full details are reported in Appendix A for data enhancement and characterisation, Appendix B for containers and Appendix C for capping and conditioning materials.

5.2.1 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 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 4.

- For legacy LHGW (shielded ILW / LLW, legacy unshielded ILW / LLW and RSCs) the stored volumes are used from the latest published UK RWI

- For HLW the UK RWI 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 copper disposal canisters for emplacement in a GDF
- For legacy nuclear materials (DNLEU, HEU, plutonium) the reported masses are used from the latest published UK RWI and split into streams based on the origin and characteristics of the material. For quantities not reported in the UK RWI (eg 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 legacy SF the reported masses are taken from the latest published UK RWI and split into streams based on the origin and characteristics of the material
- For new build waste and SF (new build shielded ILW, new build unshielded ILW, new build spent fuel), relevant published documentation (eg GDA waste disposability assessments) are reviewed for waste quantities per reactor
- 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

5.2.2 Waste material composition

Data for legacy wastes are taken from the latest UK RWI and enhanced where data requirements are not met. Data for new build wastes are taken from 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 RWI. An example is checking 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 types. 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, eg that the plastic is polyvinyl chloride (PVC).

The full detailed methodology for the review and enhancement process is reported in Appendix A2 for legacy wastes and A5 for new build waste.

5.2.3 Nuclear material and SF composition

The UK RWI only reports 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 Appendix A and a summary is included below.

- For legacy SFs (see Appendix A3) the material composition includes the fuel, cladding and other fuel assembly components that will be disposed of in a GDF. The data are sourced separately for each fuel type from publicly available information.
- Uranium and Plutonium (see Appendix A4) 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 (eg nitrates, sulphates) where the information is available

  - internal waste packaging materials of the overall disposal container 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 A5.2) the data are taken from GDA disposability assessments or the best publicly available documents. The material composition of spent fuel comprises the uranium oxide fuel, cladding and other fuel assembly components together for disposal
- For MOX SF (Appendix 0) the composition is based on discussions with the owner of the plutonium and assumptions about its 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

5.2.4 Packaging, conditioning and capping

Data for legacy wastes are taken from the latest UK RWI 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 RWM 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 RWI the data are reviewed and enhanced as described below.

There are four cases where the waste packaging is reviewed:

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

   Where the waste stream was in the previous IGD and its characteristics are unchanged then adopt that package allocation. Otherwise, consider waste packages used at the storage site as the most likely package to be used. If there is no obvious package allocation then the following rules apply

   - operational ILW streams are packaged in standard 500-litre drums except for the following:
     - compactable waste streams (eg PCM) are packaged in enhanced (annular grouted) 500-litre drums (with a pre-cast cement annulus)
     - waste streams comprising larger components unsuitable for 500-litre drums are packaged in 3 cubic metre boxes (round corners)
   - decommissioning ILW streams are packaged in 4 m ILW boxes or 3 cubic metre boxes (round corners). Comparisons are made with similar waste streams or with other waste streams from the same site

2. Waste streams where it is necessary to review the standard waste container type reported by the waste producer based on RWM's designs for a GDF:

   these enhancements are made based on information from the previous IGD where improvements or deficiencies have been identified in the dataset either from peer review, internal developments or any other area of influence[6]

3. Waste streams where a non-standard container is specified:

   - if the non-standard container is specified to be overpacked into an RWM standard container, that allocation is adopted

[6] For the last 'full' update (2013 IGD) wastes assigned to a 4 m box with 300 mm of concrete shielding were reassigned in order to make reasonable loading assumptions.

- otherwise a standard RWM disposal container is assigned after considering the packaging of similar waste streams and/or waste streams from the same site[7]; where the waste stream was in the previous IGD that allocation is also taken into account

4. Waste streams with more than one container type:

   the IGD convention is that a single container type is used per waste stream. Hence waste streams reported in the latest UK RWI that are packaged using two container types are split into two waste streams, with an 'a' and 'b' suffix. Waste volumes are allocated to the 'a' and 'b' streams on the following basis:

   - information in latest UK RWI datasheets for the waste stream
   - or a 50/50 volume split should no data be given in the latest UK RWI datasheet for the waste stream

Missing conditioning and capping data fields are enhanced following the methodology in Appendix C

Data for new build ILW are taken from GDA documents; details of the enhancements are reported in Appendix A5.

No packaging data are reported in the UK RWI for SF or nuclear materials. Illustrative package designs have been developed by RWM and Appendix B details the assumptions that have been made.

5.2.5 Radioactivity

Data for legacy wastes are taken from the latest UK RWI, radioactivities are reviewed for anomalies and, where appropriate, enhancements are made following the methodology reported in Appendix A2.3. The UK RWI currently does not include radioactivity data for nuclear materials or SF. RWM 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). RWM has made high level assumptions regarding the irradiation of each waste stream. The assumptions and method for deriving the radionuclide inventories are reported in Appendix A for each waste group.

New build ILW and SF radionuclide inventories have been taken from the GDA disposability assessment reports.

5.2.6 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. For each material component, order waste streams by their contribution to the total mass of the component.
2. Allocate material grades to steels, other metals and alloys and to proprietary material types such as exchange resins using the following order of preference:
   a. data reported in the 2013 UK RWI
   b. 2007 Derived Inventory enhancements
   c. additional information available to RWM

[7] For example, Magnox Ltd. reported the use of TRU-Shield packages for some streams in the 2016 UKRWI, for the 2016 IGD these were reassigned to 6 m^3 boxes, 500 l drums and 500 l RS drums based on packaging plans at each site.

3. Where the total mass of a material component in a waste stream is made up of a number of different grades (eg stainless steel), assign proportions to each grade.
4. Where specific material grades or types are not reported, use the same approach to allocating grades or types as was used in the 2007 Derived Inventory. (For example, where no information is available on the grade of stainless steel, it is assigned to 304L and 316 in the same relative proportion as major contributing streams where grades are reported.)
5. 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:

$$\begin{pmatrix} H \\ \vdots \\ Cf \end{pmatrix} = \sum_{n} \sum_{i} \left(m_i \times \begin{pmatrix} H_i \\ \vdots \\ Cf_i \end{pmatrix} \right)_n$$

   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, $\begin{pmatrix} H_i \\ \vdots \\ Cf_i \end{pmatrix}$ is the composition of grade i and $\begin{pmatrix} H \\ \vdots \\ Cf \end{pmatrix}$ is the total mass of each element in the waste group.

The methodology for assigning grades to the bulk materials in each waste group is reported in the appendix for each waste group.

5.2.7 Gas generation data

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

Appendix A7 shows the methodology implemented in the 2013 IGD. This method only considers reactive metals from LHGWs. HHGWs are assumed to be disposed in copper canisters, which will not corrode in near term timescales. For variant disposal containers this methodology should be reviewed.

5.3 Data management

Inventories for geological disposal comprise large amounts of data that need to be appropriately managed to ensure the required data is accessible, verified and validated.

RWM uses a purpose-built inventory database software package designed to store and analyse waste inventories. This software has been fully validated and verified at all stages of its development since its inception. All data in this report have been produced by this database software package.

5.4 Reporting

The three principal documents that describe the 2016 IGD and its implications are as follows:

Main report [4]

The Main Report also sets out the basis and scenario for the IGD. It contains the following information for each waste group:

- stored, conditioned and packaged volumes
- the number of packages and disposal units
- physical and chemical composition
- radioactivity (principally reported at time of GDF opening and closure)
- it also reports the basis and scenario for the IGD

Differences report [5]

The Differences Report sets out changes in both the IGD and the definitions of the alternative scenarios and their impacts on the 2016 IGD. Depending on the nature of the scenario and the information available, some scenarios are analysed quantitatively, some semi-quantitatively and some qualitatively:

- for each waste group the Differences report quantifies the changes and provides analysis regarding:
    - stored, conditioned and packaged volumes
    - the number of packages and disposal units
    - physical and chemical composition
    - radioactivity (principally reported at time of GDF opening and closure)
- differences in basis, assumptions and the scenario for the arising profile of each type of waste are reported
- an audit is provided of the waste streams that enter and leave the IGD either through a change in assumptions or an update to the UK RWI
- an analysis of the change in alternative scenarios of the IGD [5] is provided. This is where uncertainty in the IGD is explored and reported. There are limits to the extent on uncertainty investigation however due to the nature of assumptions underpinning each scenario. Hence some scenarios are investigated qualitatively and others quantitatively where there is information available of sufficient quality to do so

Implications report [7]

This report contains an assessment of how the changes to the IGD affect the findings of the generic DSSC. Research needs arising from the changes to the IGD are identified. It does not consider the implications for documents that sit outside of the generic DSSC.

6 Summary

The inventory for geological disposal is a snapshot in time that is an estimate of the quantities of radioactive waste destined for geological disposal based on industry plans and waste in store at the stock date. Inventory production is an iterative process and the IGD is periodically updated by the method described in this report.

The method can be summarised as:

- the basis for the IGD is given by the policies of the UK, Scottish and Welsh Governments, which define the types of waste that are destined for geological disposal
- the latest UK RWI and industry plans form the scenario of the IGD which defines a list of waste streams to be included in the IGD
- data requirements for the IGD are defined as information needed to produce RWM's designs and safety cases
- the IGD dataset is produced based on review and enhancement of the best publicly available information; principally the UK RWI and knowledge of industry plans

Although the inventory has changed significantly over time reflecting changes to the basis, scenario, data requirements and waste producers estimates; the method for production has remained relatively static as this is a well-established process. The main body of this report describes the process of compiling the IGD; the detailed assumptions are reported in the following appendices.

References

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3 Radioactive Waste Management, *Geological Disposal: Technical Background to the generic Disposal System Safety Case,* DSSC/421/01, December 2016

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6 Radioactive Waste Management, *Geological Disposal: The 2013 Derived Inventory*, DSSC/403/01, December 2016.

7 Radioactive Waste Management, *Inventory for geological disposal: Implications Report*, 2018.

8 Radioactive Waste Management, *Geological Disposal Derived Inventory: Scenarios Report*, DSSC/404/01, December 2016.

9 BEIS & NDA, *Radioactive Wastes in the UK: UK Radioactive Waste Inventory Report*, ISBN: 978-1-905985-33-3, March 2017.

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11 UK Nirex Limited, *Derived Inventory Data for the 2003 Update of the Generic Documents*, 200154.77, July 2003.

12 Welsh Government, *Welsh Government Policy on the Management and Disposal of Higher Activity Radioactive Waste*, WG23160, 2015.

13 Scottish Government, *Scotland's Higher Activity Radioactive Waste Policy 2011*, 2011.

14 Radioactive Waste Management, *Gas status report*, DSSC/455/01, 2016.

Glossary

Term	Definition
ABWR	Advanced Boiling Water Reactor. Horizon nuclear power are proposing to build UK ABWRs at Wylfa and Oldbury
AGR	Advanced Gas-cooled Reactor
AP1000	Pressurised Water Reactor sold by Westinghouse Electric Company
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.
CSA	Criticality safety assessment
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
EBS	Engineered barrier system
EPR	EPR is now used by AREVA as a reactor name, it was previously used to mean European Pressurized Reactor and Evolutionary Power Reactor
ESC	Environmental safety case
FED	Fuel element debris
GDA	Generic Design Assessment
GDF	Geological Disposal Facility
gESA	generic Environmental Safety Assessment
gOSC	generic Operational Safety Case
gTSC	Generic Transport Safety Case
GWd/tU	Gigawatt days per ton of uranium (1 ton = 1,000 kg)
GW(e)	Gigawatts electrical
HAW	Higher activity radioactive waste

HEU	Highly enriched uranium
HHGW	High heat generating waste
HLW	High level waste
IAEA	International Atomic Energy Agency
IGD	Inventory for geological disposal
ILW	Intermediate level waste
ISA	Isosaccharinic acid
ISO	International organisation for standardization
JET	Joint European Torus
LAW	Low active waste
Legacy waste	Radioactive waste which already exists or whose arising is committed in future by the operation of an existing facility
LEU	Low enriched uranium
LHGW	Low heat generating waste. Some wastes have negligible heat output; these are included in this category
LLW	Low level waste
LLWR	Low Level Waste Repository
LWR	Light Water Reactor
MBGWS	Mixed Beta Gamma Waste Store
MDU	Magnox depleted uranium
MOD	Ministry of Defence
MOX	Mixed oxide fuel
MSSS	Magnox Swarf Storage Silo
NB	New build
OESA	Operational environmental safety assessment
OPC	Ordinary Portland cement
OSC	Operational safety case
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

PCSA	Post-closure safety assessment
PCSR	Pre-construction Safety Report
PFA	Pulverised fuel ash
PFR	Prototype Fast Reactor
POCO	Post-operational clean-out
ppm	Parts per million
Priority 1 radionuclide	Highest priority score for those radionuclides having greatest effect on, wasteform, packaging, transport, criticality and GDF design
Pu	Plutonium
PVC	Polyvinyl chloride
PWR	Pressurised Water Reactor
RAL	Rutherford Appleton Laboratory
RGL	Regulatory guidance level
RPCM	Radiological protection criteria manual
RS	Robust shielded
RSC	Robust shielded container
SF(s)	Spent fuel(s): nuclear fuel removed from a reactor following irradiation that is no longer usable in its present form because of depletion of fissile material, poison build-up or radiation damage
SILW	Shielded ILW
SILW waste package	Waste package not requiring additional shielding
SLLW	Shielded LLW
SRL	Scientific readiness level: A scale calibrating the scientific maturity of underpinning science between 1 and 6 where 1 is the least mature and 6 the most established understanding
SS	Stainless steel
Superplasticiser	Commonly used to improve the flow characteristics of cements and concrete and also allow the water to cement ratio to be reduced (this produces stronger concretes). Superplasticisers could enhance the solubility of actinides
SWTC	Standard Waste Transport Container
TDC	Transport and Disposal Container
tHM	Tons of heavy metal (1 ton = 1,000 kg)

THORP	Thermal Oxide Reprocessing Plant
TPS	Transport package safety
TPU	THORP product uranium
TSC	Transport safety case
TSD	Transport system design
TSSA	Transport system safety assessment
tU	Tons of uranium (1 ton = 1,000 kg)
UILW	Unshielded ILW
UILW waste package	Waste package requiring additional shielding
UK RWI	UK radioactive waste inventory (also referred to as UK RWMI - UK radioactive waste and materials inventory)
ULLW	Unshielded LLW
VLLW	Very low level waste
WVP	Waste Vitrification Plant

Appendix A Data Enhancement and characterisation

A1 Priority materials and radionuclides

Priority scores for materials and radionuclides in the IGD were established through discussions with RWM safety case owners and experts in the areas of inventory, wasteform, packaging, transport, criticality and GDF design. The priority scores assigned to each material type and radionuclide were originally carried out in preparation of the 2004 IGD and the assignments have been reviewed for each 'full' update since. The 2016 IGD priority assignments are unchanged since the 2013 IGD as this is a 'light' update.

The priority scores have been used to determine the level of focus allocated to the enhancement of the inventory data. The priority materials and radionuclides and their scores 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.

The priority scores reflect the importance of the materials and radionuclides to RWM's safety cases, these are referred to as:

- gESA – generic Environmental Safety Assessment
- gOSC – generic Operational Safety Case
- gTSC – generic Transport Safety Case
- Criticality – Criticality Safety for waste with fissile content

Table A1 to Table A6 record the priority materials and radionuclides with their priority scores and justifications. Some materials are not relevant to certain waste types (eg organic items for HLW and SFs). Also, a small number of material and radionuclide priority scores differ for the different waste types. Where different priority scores are associated with different aspects of RWM's work areas or safety cases, the highest priority score is reported.

The priority scores are:

1. Most important
2. More important
3. Important
4. Less important
5. Least important

In the case of the priority radionuclides (Table A6), only those with a priority score of greater than or equal to 3 are listed.

Table A1 Material priorities (metals)

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type
Aluminium	Metal & carbides	gESA	2	Metal form and geometry. Extent of corrosion.	Gas pathway - corrosion produces H_2 gas. Metal carbides (C-14) may produce CH_4 / C_2H_2	ILW, LLW, SF
Magnox	Metal & metal carbides	gESA	1	Metal form and geometry. Extent of corrosion.	Gas pathway - corrosion produces H_2 gas. Metal carbides (C-14) may produce CH_4 / C_2H_2	ILW, LLW, SF
Stainless steels / mild steels	Metal & metal carbides	gESA	1	Metal form and geometry. Extent of corrosion.	Gas pathway - corrosion produces H_2 gas. Metal carbides (C-14) may produce CH_4 / C_2H_2	All
Uranium	Metal & carbides	gESA Criticality	1	Metal form and geometry. Extent of corrosion.	Gas pathway - corrosion produces H_2 gas. Metal carbides (C-14) may produce CH_4 / C_2H_2	ILW, LLW, SF, U
Zircaloy	Metal & metal carbides	gESA	2	Metal form and geometry. Extent of corrosion.	Gas pathway - corrosion produces H_2 gas. Metal carbides (C-14) may produce CH_4 / C_2H_2	ILW, LLW, SF

Table A2 Material priorities (metallic species)

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type[8]
Aluminium	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Antimony	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Arsenic	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Beryllium	All chemical forms	gESA	1	In particular metal content in key waste streams	Groundwater pathway - chemotoxic material	All
	Oxide	gOSC	5		Particulate release – toxic material. Medium release potential / mobility under accident (fire/impact) conditions	
	Oxide and metal	Criticality	3	Volume and form	Beryllium is a moderator	
Cadmium	All chemical forms	gESA	1		Groundwater pathway - chemotoxic material	All
	Metal	gOSC	1		Particulate (oxide) release – toxic material. Medium release potential / mobility under accident (fire) conditions.	All

[8] “All” comprises HLW, ILW, LLW, SF, Pu & U.

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type[8]
Caesium	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Chromium	All chemical forms	gESA	1		Groundwater pathway - chemotoxic material	All
	As soluble chromium (VI) compound	gTSC	1		Release – toxic material. High release potential / mobility under accident (immersion) conditions	All
Cobalt	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Copper	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Iron	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Lead	Oxide & carbonate	gOSC/ gTSC	1		Chemotoxic material – particulate release. Low release potential / mobility under accident (impact) conditions	All
	All chemical forms	gESA	1		Groundwater pathway - chemotoxic material	All
Magnesium	All chemical forms	gESA	1	Includes Magnox	Groundwater pathway - chemotoxic material.	All
Manganese	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type[8]
Molybdenum	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Mercury	All chemical forms	gESA	2		Groundwater pathway - chemotoxic material	All
	Element	gOSC/ gTSC	4		Vapour release – toxic material. High release potential / mobility under accident (fire) conditions	All
Nickel	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Niobium	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material Stable element inventory	All
Plutonium / Uranium	Oxide or metal	Criticality	1	Extent of corrosion (metal)	Fissile material	All
Ruthenium	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Selenium	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material Stable element inventory	All
Tin	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type[8]
Uranium	All chemical forms	gESA	1		Groundwater pathway - chemotoxic material	All
	Oxide (hydride)	gOSC/ gTSC	5	Finely divided uranium would generate hydride in waste (pyrophoric)	Particulate release – toxic material. Low (oxide) or medium (hydride) release potential / mobility under accident conditions	All
Vanadium	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Yttrium	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Zinc	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All
Zirconium	All chemical forms	gESA	3		Groundwater pathway - chemotoxic material	All

Table A3 Material priorities (organics)

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type
Cellulose (paper & cotton; wood)		gESA	1	Degrades to form ISA, acetic acid Extent of degradation The ratio of amorphous: crystalline	Groundwater pathway - degradation products affect nuclide solubility / sorption Gas pathway – microbial degradation produces gases	ILW, LLW
		gOSC/ gTSC	3	CO released by radiolytic & microbial degradation of organics; incomplete combustion of carbon (in plastics & cellulose)	Gaseous release - toxic material. High release potential / mobility under normal and accident conditions	ILW, LLW
Halogenated plastics	PVC	Criticality	3	Physical form is priority	Chlorine is a neutron absorbing material	ILW, LLW
	PVC	gOSC/ gTSC	4	HCl released on pyrolysis of PVC	Gaseous release - toxic material. High release potential / mobility under accident conditions	
Non-halogenated plastics	Polyethylene; polypropylene	Criticality	1		Neutron reflectors	ILW, LLW

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type
Organic ion-exchange resins	Styrene divinyl benzene based	gESA	1	Styrene divinyl benzene based resins can degrade to give benzene and phenol	Groundwater pathway – chemotoxic degradation products	ILW, LLW
	Anion	gOSC/ gTSC	3	Trimethylamine is a volatile organic compound released from anion exchange resins	Trimethylamine release - toxic material. High release potential /mobility under normal conditions	
	Anion	gOSC/ gTSC	3	Ammonia gas can be released from anion exchange resins	Ammonia gaseous release - toxic material. High release potential / mobility under normal conditions	
	Anion		3		Data used in wasteform research	
Other organics	Small organic molecules	gESA	1		Gas pathway – degrade to various C-14 bearing gases	ILW, LLW
	Hydrocarbon oils	Criticality	1		Neutron moderator	
	Chlorinated solvents	gOSC/ gTSC	4	Phosgene produced by combustion of chlorinated solvents	Gaseous release - toxic material. High release potential / mobility under accident conditions	

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type
Phenol	Compound (semi-volatile organic)	gOSC/ gTSC	3	Present on ICI Thoria catalyst	Vapour release - toxic material. Low release potential/mobility under normal operational and transport conditions More volatile than toluene	ILW, LLW
Plastics (general)		gESA	3		Gas pathway – microbial degradation produces gases	ILW, LLW
		gOSC/ gTSC	3	CO released by radiolytic & microbial degradation of organics; incomplete combustion of carbon (in plastics & cellulose)	Gaseous release - toxic material. High release potential / mobility under normal and accident conditions	
		gOSC/ gTSC	4	HCl released by degradation H_2S, SO_2 and HCN generated by pyrolysis.	Gaseous release - toxic material. Low release potential / mobility of HCl under normal conditions. High release potential / mobility of gases under accident conditions	
			3		Polymer encapsulants - data for wasteform research.	
		Criticality	3	Volume and form	Neutron reflectors	

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type
Toluene	Compound (VOC)	gOSC/ gTSC	3	Present on ICI Thoria catalyst. Generated from the degradation of polymers	Vapour release - toxic material. High release potential / mobility under normal operational conditions	ILW, LLW
Trichloro-ethylene	Compound (VOC)	gOSC/ gTSC	3	Present in degreasers.	Vapour release - toxic material. High release potential /mobility under normal conditions	ILW, LLW
Vinyl chloride monomer		gESA	3	Present in PVC.	Groundwater pathway – chemotoxic material	ILW, LLW
Vinyl styrene	Compound (VOC)	gOSC/ gTSC	3	Unreacted ingredient in polymer encapsulant used at Trawsfynydd	Vapour release - toxic material. Medium release potential /mobility under normal conditions	ILW, LLW

Table A4 Material priorities (inorganic anions)

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type
Borate		gESA	3		Groundwater pathway – chemotoxic material	ILW, LLW
Fluoride		gESA	3		Groundwater pathway – chemotoxic material	ILW, LLW
Nitrate		gESA	2	Inhibits the production of methane (and hence C-14)	Groundwater pathway – chemotoxic material	ILW, LLW
Nitrite		gESA	1		Groundwater pathway – chemotoxic material	ILW, LLW
Phosphate		gESA	3		Groundwater pathway – chemotoxic material	ILW, LLW
Selenate		gESA	3		Groundwater pathway – chemotoxic material	ILW, LLW
Sulphate		gESA	2	Inhibits the production of methane (and hence C-14)	Groundwater pathway – chemotoxic material	ILW, LLW
Sulphide		gOSC/ gTSC	4	H_2S generated by microbial action on sulphates in waste)	H_2S gaseous release - toxic material. Medium release potential / mobility under normal conditions	

Table A5 Material priorities (others)

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type
Ammonium species	Compound	gOSC/ gTSC	3	Ammonia gas can be released from ammonium-based precipitates	Gaseous release - toxic material. High release potential / mobility under normal conditions	ILW, LLW
Asbestos		gOSC/ gTSC	5		Particulate release – toxic material. Medium release potential / mobility under accident (impact) conditions	ILW, LLW
Eutectics (eg $BaCl_2$)	Compound	gOSC/ gTSC	5		Particulate release - toxic material. Medium release potential / mobility under accident (impact followed by fire) conditions	ILW, LLW
Ferrocyanates	Compounds	gOSC/ gTSC	4	HCN can be produced from reactions in waste	Gaseous release - toxic material. Low release potential / mobility under normal conditions	ILW, LLW
Graphite		gESA	2	C-14 content Cl36 content (due to relatively high concentrations)	Gas pathway – produces C-14 bearing gas	ILW, LLW
		Criticality	1	Volume and form	Graphite is a neutron moderator	ILW, LLW

Inventory Item	Material / compound / element	Safety Case	Priority Score	Comments / Other information required	Justification	Waste/ material type
Non-aqueous phase liquids (NAPLs)		gESA	3		Groundwater pathway - affects nuclide solubility / sorption	ILW, LLW
Potassium hydroxide		gOSC/ gTSC	5	From liquid metal residues in waste	Particulate release – toxic material. Medium release potential / mobility under accident (fire) conditions	ILW, LLW

Table A6 Radionuclide priorities

Parent radionuclide[9]	Safety case	Pathway / Situation	Priority score[10]	Waste/ material type
H-3	gOSC	Accident	3	ILW/LLW
C-14	gESA; gOSC	Gas	1	HLW, ILW, LLW, SF
Cl-36	gESA	Groundwater	1	HLW, ILW, LLW, SF
Co-60	gOSC; gTSC	Accident; Operational; Worker doses	1	HLW, ILW, LLW, SF
Ni-59	gESA	Groundwater	3	HLW, ILW, LLW, SF
Ni-63	gOSC	Operational	3	HLW, ILW, LLW, SF
Se-79	gESA	Groundwater	1	HLW, ILW, LLW, SF
Kr-85	gOSC	Gas	1	HLW, SF, U & Pu
Sr-90	gOSC	Accident; Operational	3	HLW, ILW, LLW, SF
Zr-93/Nb-93m	gESA	Groundwater	3	HLW, ILW, LLW, SF
Nb-94	gESA; gTSC	Human Intrusion; Worker doses	3	HLW, ILW, LLW, SF
Mo-93	gESA	Groundwater	3	HLW, ILW, LLW, SF
Tc-99	gESA	Groundwater	1	HLW, ILW, LLW, SF

9 All radionuclides listed are included in the 2016 UK RWI.

10 The reason for the priority scores only going down to 3 is that the radionuclides listed in Table A6 are a sub-set of the 112 radionuclides identified as relevant to long-term waste management in the UK. The radionuclides not listed because they play no part in the focused data review and enhancement exercise would fall into priority levels 4 and 5.

Parent radionuclide[9]	Safety case	Pathway / Situation	Priority score[10]	Waste/ material type
Sn-126	gESA	Groundwater	2	HLW, ILW, LLW, SF
I-129	gESA	Groundwater	1	HLW, ILW, LLW, SF
Cs-135	gESA	Groundwater	1	HLW, ILW, LLW, SF
Cs-137	gOSC; gTSC	Accident; Operational; Worker doses	1	HLW, ILW, LLW, SF
Eu-152	gOSC	Operational; Worker doses	3	HLW, ILW, LLW, SF
Eu-154	gTSC	Worker doses	3	HLW, ILW, LLW, SF
Th-232	gESA	Groundwater	3	HLW, ILW, LLW, SF- radionuclides yielding risk: Ra-228, Th-228
Th-234	gTSC	Worker doses	3	ILW/LLW & HLW/SF
Pa-231	gESA	Groundwater	2	HLW, SF, U, Pu
U-233	Criticality	Accident; Operational	1	HLW, ILW, LLW, SF
U-234	gESA	Groundwater	2	HLW, ILW, LLW, SF, U
U-235	gESA; Criticality	Groundwater	1	HLW, ILW, LLW, SF, U - radionuclides yielding risk: U-235; Ac-227; Pa-231
U-236	gESA	Groundwater	3	HLW, ILW, LLW, SF
U-238	gESA; Criticality	Groundwater; Human Intrusion	1	HLW, ILW, LLW, SF, U - radionuclides yielding risk: Pb-210, Ra-226; Th-230; U-238; Rn-222

Parent radionuclide[9]	Safety case	Pathway / Situation	Priority score[10]	Waste/ material type
Np-237	gESA	Groundwater	1	HLW, ILW, LLW, SF - radionuclides yielding risk: Th-229; U-233; Np-237
Pu-238	gOSC	Accident; Operational	2	HLW, ILW, LLW, Pu
Pu-239	gESA; gOSC; Criticality	Human Intrusion	2	HLW, ILW, LLW, Pu
Pu-240	gESA; gOSC	Human Intrusion; Accident; Operational	2	HLW, ILW, LLW, Pu
Pu-241	gOSC	Accident; Operational	2	HLW, ILW, LLW, Pu
Pu-242	gESA		3	HLW, ILW, LLW, Pu
Am-241	gESA; gOSC; gTSC	Human Intrusion; Accident; Operational; Worker doses	3	ILW/LLW & HLW/SF
Am-242m	gOSC	Accident; Operational	3	ILW/LLW & HLW/SF
Cm-244	gOSC; gTSC	Worker doses	3	ILW/LLW & HLW/SF
Cm-248	gTSC	Worker doses	3	ILW/LLW & HLW/SF

A2 Legacy wastes

A2.1 Bulk material composition

A2.1.1 Level 1 and Level 2 materials

The UK RWI 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 A7 lists these materials.

There is some overlap between these bulk materials (eg 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)

  The sum of the mass of all level 1 materials within a waste stream should[11] 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 A7 contains the bulk components reported numerically in the 2016 UK RWI 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 RWI for additional materials to be quantified in the IGD. This review and enhancement process is detailed in the following section.

Table A7 Chemical components for which the 2016 UK RWI contains numerical data

Metals and alloys	Organics	Inorganics
Aluminium (and alloys[12])	Cellulose (total)	Inorganic ion exchange materials
Beryllium	Cellulose (paper & cotton)	Inorganic sludges and flocs
Cobalt (and alloys[13])	Cellulose (wood)	Soil
Copper (and alloys[14])	Halogenated plastics	Brick/Stone/Rubble
Lead	Non-halogenated plastics (total)	Cementitious material

11 Note: the word *should* is used as although UK RWI 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 Section A2.1.2, although it is not always possible depending on the information submitted to the UK RWI.

12 Alloys include: Boral, Dural.

13 Alloys include: Stellite.

14 Alloys include: Brass, Bronze.

Metals and alloys	Organics	Inorganics
Magnox/Magnesium	Non-halogenated plastics (condensation polymers)	Sand
Nickel (and alloys[15])	Non-halogenated plastics (others)	Glass/Ceramics
Other ferrous metals[16]	Organic ion exchange materials	Graphite
Stainless Steel	Rubber (total)	Desiccant/Catalyst
Titanium	Rubber (Halogenated rubber)	Asbestos
Uranium	Rubber (Non-halogenated rubber)	Chrysotile (asbestos)
Zinc	Other organics	Amosite (asbestos)
Zircaloy/Zirconium		Crocidolite (asbestos)
Other metals[17]		Free aqueous liquids[18]
		Free non-aqueous liquids
		Powder/Ash

A2.1.2 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 RWI and, "where appropriate", making quantitative assumptions. The methodology is detailed below:

1. 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 RWI 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 RWI conventions define 'TR' as in the range 1 – 100 ppm. In the 2007 IGD [A1] the best estimate component composition was assigned a value of 0.001% (ie equivalent to a geometric mean of 10 ppm). A review of the data in the 2013 UK RWI showed that applying this methodology would only add ~15 tonnes to the total mass of legacy ILW (ie ~0.005%) and no

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15 Alloys include: Inconel, Nimonic, Monel.

16 Alloys include: Mild Steel, Cast Iron.

17 Includes: Cadmium.

18 Additional to water associated with wet wastes (sludges, flocs and ion exchange materials).

more than 1% to any one material component. Because these impacts are 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 RWI to identify any Level 1 materials in Table A7 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 (ie 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, steel 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 RWI.
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 RWI 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 RWI 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 RWI 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 RWI that are not in the previous IGD and incorporate any data
9. Any mass not allocated to a specific material remains unassigned.
10. Upper and lower uncertainties in material component masses are calculated by using the upper and lower uncertainty factors on waste stream volumes reported in the UK RWI.

HLW

HLW streams are made up of calcined waste oxide in a borosilicate glass matrix within stainless steel waste vitrification plant (WVP) canisters, with the exception of high level contaminated plant items (stream 2F22/C), which comprise Inconel, Uranus 65 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 RWI do not include the stainless steel WVP canister and only describe the stored 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 RWI 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. The mass comprises approximately 100 kg of waste oxide and approximately 300 kg of borosilicate glass.

The composition assumed for the waste oxide is given in Table A8 [A2], while the composition of the glass is given in Table A9 from information in the UK RWI. The WVP canister has a mass of about 85 kg and is manufactured from Type 309 stainless steel.

Table A8 Composition of waste oxide (%)

Species	Mass (%)	Species	Mass (%)	Species	Mass (%)
GeO_2	$9.2\ 10^{-4}$	Rh_2O_3	1.80	CeO_2	8.80
As_2O_3	$2.6\ 10^{-4}$	PdO	4.02	Pr_6O_{11}	3.95
SeO_2	0.202	Ag_2O	0.192	Nd_2O_3	13.3
Rb_2O	1.08	CdO	0.215	Pm_2O_3	0.204
SrO	2.78	In_2O_3	$6.39\ 10^{-3}$	Sm_2O_3	2.65
Y_2O_5	1.64	SnO_2	0.232	Eu_2O_3	0.389
ZrO_2	13.8	Sb_2O_3	$4.12\ 10^{-2}$	Gd_2O_3	0.230
Nb_2O_5	$5.18\ 10^{-5}$	TeO_2	1.31	Tb_2O_3	$6.91\ 10^{-3}$
MoO_3	14.1	Cs_2O	8.37	Dy_2O_3	$2.07\ 10^{-3}$
TcO_2	3.23	BaO	5.03		
RuO_2	7.87	La_2O_3	4.16		

Table A9 Composition of the glass used to vitrify HLW (%)

Material	SiO_2	Na_2O	B_2O_3	Li_2O
Glass	62.9	11.4	23.0	2.7

A2.2 Elemental composition

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

1. For each material component, order waste streams by their contribution to the total mass of the component.
2. Allocate material grades to steels, other metals and alloys and to proprietary material types such as exchange resins using the following order of preference:
   - data reported in the UK RWI
   - IGD enhancements
   - additional available information
3. Where the total mass of a material component in a waste stream is made up of a number of different grades (eg stainless steel), assign proportions to each grade.

4. Where specific material grades or types are not reported and no information is available it is assigned as a mix of grades or types in the relative proportion as major contributing streams where grades are reported.
5. For sludge streams from corroded and dissolved Magnox and UO_2 waste forms, the magnesium mass in $Mg(OH)_2$ sludges are scaled to the source Magnox alloy elemental composition, and the uranium mass in UO_2 to the source uranium elemental composition.
6. Once material grades have been established for all of the components, the elemental masses are determined using a database of elemental precursor compositions (see section 5.2.6).

A2.3 Radionuclide composition

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

The review of the data 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 RWI.

The following methodology is used.

1. Limit the review and enhancement work to the 37 priority radionuclides in Table A6.
2. Identify other additional sources of public domain data (eg reports from RWM'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 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 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 next UKRWI
4. Identify gaps in the data for waste streams that do not contribute to radionuclide totals (because activity is not quantified). Filter out gaps for small volume waste streams that contain insignificant activities.
5. Focus enhancement work on the more significant gaps in activities (ie for each radionuclide 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 latest UK RWI 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’[19] reported in the UK RWI. 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 are carried out. This includes the calculation of total radionuclide activity changes and a review of radionuclide ratios.

[19] Activities of radionuclides are reported in the UK RWI with an associated code to indicate how the data have been produced (eg 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.

A3 Legacy SFs

The UK RWI only includes masses of legacy SFs. For each fuel type, material and radionuclide compositions need to be calculated and a packaging concept assigned.

The enhancement approach is to use information compiled for the previous IGD that remains valid together with improved characterisation data where available.

It has been necessary to calculate radionuclide inventories for these fuels using the outputs from internationally recognised software (eg 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 these key input parameters:

- use the most recent data / calculations available that may be publicly referenced, taking note of what has been adopted by RWM for packaging assessment work
- 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 radionuclide specific activity data for SF streams have been taken from a number of sources. These are based on the use of fresh (ie not recycled) uranium for fuel manufacture, and an appropriate burnup for each fuel type.

In the case of SFs, no uncertainty data for the characterisation of the waste have been derived; to do so would require considerable analysis and calculation that is beyond the scope of this work. Uncertainties in the quantities of SFs are explored through alternative inventory scenarios [A3, A4]. There are a number of factors that contribute to uncertainty in the radionuclide data, including:

- fuel burnup and uranium enrichment assumptions
- underlying data within the given simulation code used to calculate SF inventories
- the shorter irradiation period for the final reactor charge fuel (this has not been accounted for, but the impact will be small)
- use of recycled uranium in fuel (some AGR fuel has been manufactured from Magnox reprocessed uranium and so will have a different initial uranium isotopic composition)
- varying levels of impurities (eg chlorine and nitrogen) in the fuel and cladding

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

A3.1 AGR SF

Bulk materials

Spent fuel bulk materials are quantified with respect to their assumed disposal container. Details of the packaging assumptions are provided in Appendix B2.1 and Table A10 which presents the assumed fuel composition.

Table A10 AGR SF components in a disposal container

Component	Material	Mass (t)
Fuel	UO_2 (U)	2.34 (2.06)
Cladding	Type 20/25 Nb SS	0.282[20]
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 composition

It is assumed that the SF remaining unreprocessed is that which has been most recently discharged from reactors. Based on details of AGR SF in storage in the Sellafield ponds, the AGR SF inventory calculations assume a burn-up of 28 GWd/tU and an enrichment of 2.9% for fuel irradiated pre-2013 (1.4.2013) with an average cooling time of 9 years to 1.4.2016.

It is assumed that AGR fuel, irradiated post-2013 until all AGRs shutdown can be divided evenly into two enrichments (3.2% and 3.78%) [A5], each with a burn-up of 33 GWd/tU.

The other irradiated components of the AGR SF that are disposed with the UO_2 are assumed to be irradiated to 47.4 GWd/tU. The apparent discrepancy between the burn-up assumed for the fuel and that assumed for the other components is considered to be insignificant. In addition, the impurities in the components and fuel are assumed to be present at the maximum permissible level, with the exception of nitrogen in the stainless steel cladding. Nitrogen is an important precursor for C-14 and RWM's C-14 integrated project team has undertaken work to determine the concentration of the nitrogen precursor. Based on discussions with members of the C-14 integrated project team, the concentration of nitrogen in the stainless steel is assumed to be 100 ppm.

Table A11 The key parameters used in the calculation of AGR SF radionuclide inventory

Fuel[21]	Burn-up (GWd/tHM)	Enrichment (%)	Cooling times (yrs)
AGR (pre-2013)	28	2.9	9
AGR (post-2013)	33	3.2 / 3.78[22]	1[23]

20 Consistent with the 2007 IGD, for the radionuclide activity of AGR SF it is assumed that there is 0.27 t cladding.

21 Fuel types are differentiated by pre-2013 and post-2013 because data are carried over from the 2013 IGD.

22 There are two enrichments for the 'robust fuel', which are assumed to be used in equal amounts.

A3.2 Sizewell B SF

Bulk materials

Spent fuel bulk materials are quantified with respect to their assumed disposal container. Details of the packaging assumptions are provided in Appendix B2.1. Table A12 presents the assumed fuel composition.

Table A12 PWR SF components in a disposal container

Component	Material	Mass (t)
Fuel	UO_2 (U)	2.08 (1.834)
Cladding[24]	Zircaloy 4	0.4688
Plenum springs	Type 304 SS	$9.60\ 10^{-3}$
Grids	Inconel 718	$2.68\ 10^{-2}$
Grid sleeves	Type 304 SS	$4.80\ 10^{-3}$
Top & bottom nozzles[25]	Type 304 SS	$5.04\ 10^{-2}$

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 composition

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 A13. Sizewell B SF pre-2013 is assumed to have a burn-up of 45 GWd/tU, an enrichment of 4.2% and an average cooling time of 11 years. Sizewell B SF post-2013 is assumed to have a burn-up of 55 GWd/tU and an enrichment of 4.4%.

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 61 GWd/tU. The apparent discrepancy between the burn-up assumed for the fuel and that assumed for the other components is assumed to be insignificant.

Table A13 The key parameters used in the calculation of PWR SF radionuclide inventory

Fuel	Burn-up (GWd/tHM)	Enrichment (%)	Cooling times (yrs)
Sizewell B (pre-2013)	45	4.2	11

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23 For fuel arisen in between 2013 and the stock date (1.4.2016) the cooling time is 1, 2 and 3 years for fuel arisen in 2015, 2014 and 2013.

24 Note that for the post-2013 Sizewell B fuel the cladding is assumed to be M5 and not Zircaloy 4.

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

Fuel	Burn-up (GWd/tHM)	Enrichment (%)	Cooling times (yrs)
Sizewell B (post-2013)	55	4.4	1[23]

A3.3 Exotic SFs

The data (including quantities, materials and radionuclide inventory) for exotic SFs are based solely on PFR SF. This is known to be an incorrect assumption and uncertainty over the types and quantities of exotic SFs will remain until THORP operations cease in 2018. Once THORP ceases operations, further data may become available. The characterisation is continually reviewed and what is presented below represents the current assumptions.

Bulk materials

PFR SF comprises intact sub-assemblies and separate fuel pins. The sub-assemblies contain driver fuel and additional breeder material. The driver fuel is a (U, Pu)O_2 solid solution known as mixed oxide (MOX). The plutonium content is typically 25 – 33% plutonium by mass and it is assumed that the PFR fuel is 29.5% plutonium by mass. The breeder material comprises depleted UO_2.

There is considerable variety between individual fuel sub-assemblies. Each sub-assembly contains between 165 and 325 fuel pins, with the number of pins depending on their diameter. From data published by IAEA [A6], the quantity of uranium and plutonium in seven unirradiated sub-assemblies is estimated to be ~600 kgHM. High burn-up results in a significant reduction in the quantity of heavy metals in the fuel after irradiation and therefore it is assumed that a disposal container with seven sub-assemblies would contain ~550 kgHM.

Some fuel sub-assemblies are clad in a stainless steel wrapper, others in a Nimonic wrapper. Similarly, individual fuel pins are clad in stainless steel or Nimonic. Currently there are insufficient detailed data for the PFR sub-assemblies and fuel pins to accurately calculate the quantities of stainless steel and Nimonic. It has been assumed that for each tonne of heavy metal, there is 0.302 t of Nimonic cladding. This is an upper value for sub-assemblies with 325 fuel pins. The total materials mass in a PFR disposal container is shown in Table A14.

Table A14 PFR SF components in a disposal container

Component	Material	Mass (t)
Fuel	UO_2 / PuO_2 (U/Pu)	0.624 (0.550)
Cladding	Nimonic	0.166
SS canisters	Type 304 SS	0.488

Elemental composition

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

Radionuclide composition

Spent PFR fuel assemblies have a wide range of irradiation histories with cumulative burn-ups ranging from 21 GWd/tHM to 230 GWd/tHM [A7]. The most recent PFR fuel inventories are for burnups of 95 GWd/tHM and 189 GWd/tHM. A burn-up of 189 GWd/tHM has been used when determining the PFR SF inventory (Table A15).

Table A15 The key parameters used in the calculation of Exotic SF radionuclide inventory

Fuel	Burn-up (GWd/tHM)	Enrichment (%)	Cooling times (yrs)
Exotic SFs stocks	189	(Pu) 29.5	22

A3.4 Metallic SFs

The data (including quantities, materials and radionuclide inventory) for metallic SFs are based solely on Magnox SF. The characterisation is continually reviewed and what is presented below represents the current assumptions.

Bulk materials

Sufficient information is not currently available to determine the material components of the legacy ponds fuel. To allow some contribution from these fuels in the IGD, it is assumed that the composition is the same as that for Magnox SF, which is expected to be the predominant component of the fuel.

Details of the materials and masses of the components contained within a single disposal container (corresponding to 26 intact fuel elements in each of three WVP-type canisters) are given in Table A16. The fuel and cladding data are average values for five fuel element designs that could potentially be packaged rather than reprocessed. The mass of the WVP type canisters is assumed to be 127 kg.

Table A16 Assumed legacy ponds fuel components in a disposal container

Component[26]	Material	Mass (t)
Fuel	Uranium metal	0.886
Cladding[27]	Magnox AL80	0.159
WVP canisters	Type 309 SS	0.381

Elemental composition

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

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

27 Mass includes stainless steel sheathed bottom cone (mass unknown).

Radionuclide composition

The radionuclide composition of the legacy ponds fuels is calculated based on the irradiation of Magnox fuel (natural uranium) irradiated to 4.1 GWd/tU, the parameters assumed for calculation of the Metallic SF inventory are reported in Table A17.

Table A17 The key parameters used in the calculation of Metallic SF radionuclide inventory

Fuel	Burn-up (GWd/tHM)	Enrichment (%)	Cooling times (yrs)
Metallic SFs stocks	4.1	0.71	39

A4 Uranium and plutonium

The UK RWI only includes 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.

The enhancement approach is to use information compiled for the previous IGD that remains valid together with improved characterisation data where available. The characterisation data presented below represents the current assumptions.

A4.1 Uranium

Bulk materials

Uranium is stored in a number of 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 A18 Uranium waste streams in the 2016 IGD

Waste Stream ID	Waste Group	Waste Stream Description	Assumed chemical form for disposal
MU001	HEU	HEU from civil nuclear programmes	UO_2
MU002	HEU	HEU from defence programmes	UO_2
MU005	DNLEU	THORP product Uranium	U_3O_8
MU009	DNLEU	DU from defence enrichment	U_3O_8
MU012	DNLEU	Miscellaneous DNLEU	U_3O_8
MU013	DNLEU	Magnox depleted uranium (in overpacked 200 l mild steel drums)	UO_3
MU014	DNLEU	Magnox depleted uranium (in 210 l stainless steel drums)	UO_3
MU015	DNLEU	DU tails (unirradiated) in DV-70	U_3O_8
MU016	DNLEU	DU tails (irradiated) in DV-70	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 A18. The bulk material composition of the wasteform is therefore 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." 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 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.
- Based on the specification for U_3O_8 produced in the Tails Management Facility, the uranyl fluoride (UO_2F_2) content of material deconverted from uranium hexafluoride (UF_6) tails derived from unirradiated uranium is assumed to be 4 wt%. This is likely to be a conservative 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 nominal value of 0.03 µg/gU is assumed – a measured datum for THORP product uranium (TPU).
- The Magnox depleted uranium (MDU) UO_3 specification for recycled material [A8] provides limits on some contaminants (see Table A19). 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 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 A19 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 composition

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 are available for the THORP reprocessing plant only (see Table A20). These factors have also been used for determining radionuclide impurity levels in MDU. Mean decontamination factors 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 A20 Uranium decontamination factors (DF) for THORP[28]

Contaminant	Observed DF to UO_3 product	Mean DF
Tc-99	8.17 10^3 – 1.16 10^4	9.74 10^3
Ru-106	4.32 10^6 – 1.33 10^7	7.58 10^6
Cs-134 + Cs-137	5.66 10^9 – 1.38 10^{10}	8.84 10^9
Ce-144	9.36 10^5 – 4.96 10^6	2.15 10^6
Np-237	3.31 10^4 – 6.76 10^4	4.73 10^4
Plutonium isotopes	8.60 10^6 – 2.03 10^7	1.32 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. For the purposes of the 2016 IGD, only U-236 (0.03% of mass of uranium) and Np-237 (1 Bq per gU) are quantified.

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.

A4.2 Plutonium

Material composition

The IGD includes some separated civil plutonium for geological disposal (that which is not suitable for re-use as MOX fuel); 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 (eg nitrate) and trace metallic species from the corrosion of process equipment (eg 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.

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28 Where decontamination factors can be compared with impurity levels in UO_3 product, they have been shown to be consistent.

Plutonium therefore continues to be reported without impurities as no definitive data are available.

Radionuclide composition

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 (ie 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 (ie the initial composition of the feed to the chemical separation plant) and reported mean decontamination factors that quantify the performance of the plant [A9]. The following decontamination factors are used:

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

A5 New build

The UK RWI does not contain estimated quantities of new build wastes. The source and justification for the use of inventory information on these wastes and SFs are based on the Implementing Geological Disposal White Paper [A10] and are detailed below. Operational and decommissioning wastes are considered separately to SFs. Operational wastes are assumed to arise at a constant rate from reactor start-up to final reactor shut-down. It is assumed that transport of new build decommissioning wastes to the GDF begins 40 years after reactor shutdown [A11, A12]. The arisings of SFs are assumed to be equally distributed over the 60 year lifetime of the reactors.

The assumptions regarding the number of new build reactor types and their dates of operation will be set out in the IGD scenario (see Section 3). Consistent with the 2013 IGD, the 2016 IGD assumes six EPRs and six AP1000s to meet the industry ambition of 16 GW(e) from a new build programme. The following sub-sections report data for ILW and spent fuel from the UK EPR and AP1000.

A5.1 ILW

A5.1.1 UK EPR

Wastes destined for geological disposal from the UK EPR are estimated in the GDA disposability assessment report [A11]. The Operational and decommissioning ILW waste streams defined for the UK EPR in the GDA and are reported in Table A21.

Unconditioned volumes and the numbers of disposal containers for operational waste have been taken from the GDA PCSR [A13] and from NDA's GDA disposability assessment [A14] for decommissioning waste. Conditioned and packaged volumes are derived from the number of disposal containers [A11] and the container payload and displacement volumes (see section B1.3).

Table A21 Operational and decommissioning ILW from the UK EPR

Waste stream	Description
EP01	Ion exchange resin
EP02	Spent cartridge filters (ILW)
EP03	Spent cartridge filters (ILW + LLW)
EP04	Operational waste > 2 mSv/hr
EP05	Wet sludge
EP301	Decommissioning: reactor vessel
EP302	Decommissioning: Upper and Lower reactor internals
EP303	Decommissioning: Lower reactor internals including heavy shield

A5.1.2 AP1000

Wastes destined for geological disposal from the AP1000 are estimated in the GDA disposability assessment report [A12]. The Operational and decommissioning ILW waste streams defined for the AP1000 in the GDA and are reported in Table A22.

Information on the numbers of waste packages and volumes of operational and decommissioning wastes has been taken from the NDA's GDA disposability assessment report [A12]. Conditioned and packaged volumes are derived from the number of disposal packages [A12] and the container payload and displacement volumes (see section B1.3).

Table A22 Operational and decommissioning ILW from the AP1000

Waste stream	Description
AP01	Primary circuit filters
AP02	Primary resins
AP03	Secondary resins
AP301	Decommissioning: ILW steel
AP302	Decommissioning: Pressure vessel

A5.1.3 Material composition

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

1. Use material components and grades given in the reference documents for the UK EPR [A11, A14] and AP1000 [A12, A15].
2. Where information is not available, assume the same compositions as equivalent streams from the Sizewell B PWR.

The redundant non-fuel core components (eg rod cluster control assemblies and thimble plugs) were not considered in the GDA work. As a result, no information is available on these components and they are not included in the IGD.

A5.1.4 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.

A5.1.5 Radionuclide composition

Radionuclide inventories for the UK EPR and AP1000 have been taken from the GDA disposability assessment reports [A16 A17.

A5.2 SFs

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 a sensitivity study.

Both the UK EPR and the AP1000 are assumed to discharge fuel with a burn-up of 65 GWd/tU. The radionuclide inventories for the SFs have been taken from the GDA reports and, for simplicity, the total arisings of the SFs are assumed to be equally distributed over the operational lifetime of the reactors. It is assumed that the SFs are disposed of directly, with three SF assemblies in a single disposal container [A18].

The 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 [A19]. 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.

For the AP1000, the NDA's GDA disposability assessment report estimates 640 disposal containers each containing four fuel assemblies with a burn-up of 65 GWd/tU over a reactor lifetime. However, this is a very conservative estimate[29] and a more realistic inventory of SF has been derived based upon the equivalent data for the UK EPR.

The fuel used for the AP1000 is very similar in geometry and composition to that used in the UK EPR. For a given fuel burn-up the heat output characteristics of the two fuel types would be very similar. Thus, it is found that an AP1000 reactor would generate 620 disposal containers, each containing three SF assemblies[30].

A5.2.1 Material composition

The material composition of the SF assemblies is given in the GDA disposability assessment reports [A11, A14, A12, A15] and Table A23 and Table A24 show the mass of each of the components that are present in a disposal container (ie equivalent to three SF assemblies).

Table A23 UK EPR SF components in a disposal container

Component	Material	Mass (t)
Fuel	UO_2 (U)	1.79 (1.58)
Cladding, grids & guide tubes within active region	Zircaloy M5	0.438
Cladding, grids & guide tubes outside active region	Zircaloy M5	$3.39\ 10^{-2}$
Upper & lower plug for fuel pin	Zircaloy M5	$3.87\ 10^{-3}$
Additional zircaloy M5 mass	Zircaloy M5	$1.03\ 10^{-2}$
Inconel 718 grid spring within active zone	Inconel 718	$1.98\ 10^{-3}$
Top nozzle spring	Inconel 718	$3.90\ 10^{-3}$
Plenum springs	Inconel 718	$7.20\ 10^{-3}$
Top & bottom nozzle	ALSL 304 L St. Steel	$4.38\ 10^{-2}$
Alumina insulating pellets	Al_2O_3	$1.79\ 10^{-3}$

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29 The estimate in the GDA disposability assessment reports contains the maximum number of fuel assemblies (derived assuming a burn-up of 50 GWd/tU) and the maximum radionuclide inventory (derived assuming a burn-up of 65 GWd/tU).

30 This estimate is based on the ratio of the output electrical energy (1.14 / 1.6) of the two reactors which is assumed to reflect the ratio of the thermal outputs of the two reactors.

Table A24 Spent AP1000 fuel components in a disposal container

Component	Material	Mass (t)
Fuel	UO_2 (U)	1.84 (1.62)
Cladding	Zirlo	0.374
Cladding, grids & guide tubes outside active region	Zirlo	8.79 10^{-2}
Upper & lower plug for fuel pin	Inconel 718	6.21 10^{-3}
Additional zircaloy M5 mass	Inconel 718	3.87 10^{-3}
Inconel 718 grid spring within active zone	St Steel Type 304	4.37 10^{-2}
Top nozzle spring	Zirlo	6.93 10^{-3}
Plenum springs	Inconel 718	5.46 10^{-3}
Top & bottom nozzle	Al_2O_3	1.70 10^{-3}

A5.2.2 Elemental composition

The material grades and masses reported in Table A23 and Table A24 are used to calculate the elemental composition of the disposed waste. The fuel is assumed to be unirradiated with no impurities.

A5.2.3 Radionuclide composition

Radionuclide inventories for the UK EPR and AP1000 have been taken from the GDA disposability assessment reports; the inventories include volumes and radionuclide inventories for ILW and SF. Parameters assumed in calculations are reported in Table A25, and each reactor lifetime is 60 years. Fuel arisings are split evenly over each year of the lifetime of each reactor.

Table A25 The key parameters used in the calculation of new build SF radionuclide inventory [A11, A12]

Fuel	Burn-up (GWd/tHM)	Enrichment (%)	Cooling times (yrs)
UK EPR arisings	65	5.0	1
AP1000 arisings	65	4.5	1

A6 MOX SF

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

A6.1.1 Material composition

The illustrative calculations assume that the fuel is irradiated in a PWR, and since the parameters for the AP1000 and UK EPR fuel assemblies are similar, it has been decided to base the MOX fuel assemblies on the AP1000 and the UK EPR fuel assemblies. The parameters have been chosen as follows:

- The heavy metal mass per assembly are the same as that in an AP1000 [A12] fuel assembly; this maximises the inventory of fission products in a disposal container.
- The amounts of cladding and other assembly components are the same as that in a UK EPR [A11]; this maximises the inventory of activation products in a disposal container.

A summary of the material content of a MOX fuel assembly is presented in Table A26.

Table A26 MOX fuel assembly components used for calculations

Material	Mass (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	$5.95\ 10^{-4}$

A6.1.2 Elemental composition

The material grades and masses reported in Table A26 are used to calculate the elemental composition of the disposed waste, the fuel was assumed to be unirradiated with no impurities.

A6.1.3 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%
- Am-241 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 (roughly half-way between an AP1000 (40.1 MW/tHM) and a UK EPR (35.4 MW/tHM)[31]).

31 AP1000 and UK EPR ratings derived from data in the GDA disposability assessment reports [A11, A12].

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 assumed to be insignificant.

A7 Gas generation data

The parameters required for the gas generation calculations are not calculated in a 'light' update, this section describes the method used to calculate the gas generation data for a 'full' update. This method only considers reactive metals from LHGW.

A7.1 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 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 RWI. 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 RWI 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 RWI 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 (Appendix B contains details). The stainless steel stillages disposed of with the 500 l drums are also taken into account.

As the UK RWI does not contain waste streams from new build reactors the methodology is to review publicly available reference material, and where no data can be found to adopt the equivalent data for Sizewell B waste streams. The outcome has been to adopt Sizewell B data for operational ILW streams (though the mass of metal in the operational ILW streams is very low) and specific data for the UK EPR and AP1000 reactor for decommissioning wastes [A20 A21].

A7.2 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.

A7.2.1 Method to calculate C-14 by material type

The approach to the analysis comprises the following stages:

1. Rank waste stre
2. ams in order of total C-14 activity. Priority is given to streams that are the major contributors to the total C-14 activity. (Approximately 90% of the C-14 activity is in the top 20 waste streams that contribute to the C-14 activity.)
3. Assign streams to a list of 12 material types (shown in Table A27).
4. 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.

Table A27 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
MX – corroded	Magnox alloy corrosion products most likely to be $Mg(OH)_2$
U – corroded	Uranium metal corrosion products, ie UOx
Non Metal	Materials such as desiccant, ion exchange resin and barium carbonate arising from THORP operations
GEH	Specific GE Healthcare waste streams rich in C-14 (1A07 & 1B05)
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 50^{th} 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 [A22] 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

A number of 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 RWI generally does not quantify the fraction of uranium and Magnox metal that has been subject to corrosion while in wet storage. However, for the five MSSS streams (2D08, 2D09, 2D22, 2D24 and 2D35), 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 A28).

4. Develop estimates where waste streams contain irradiated U and Magnox metal but do not have C-14 activity values.
5. 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 2013 IGD).

Table A28 The fraction of the reactive metals that are corroded in the 2013 IGD

Waste Stream ID	Material	Uncorroded (% of stream)	Corroded (% of stream)	Uncorroded + corroded (% of stream)	Corrosion factor [corroded / (uncorroded + corroded)]
2D08	Magnox	3.0	38.8	41.8	0.928
2D09	Magnox	6.0	38.0	44.0	0.864
2D24	Magnox	25.3	17.3	42.6	0.406
2D22	Magnox	21.0	25.1	46.1	0.544
2D35	Magnox	79.4	15.3	94.7	0.162
2D08	Uranium	1.0	1.7	2.7	0.630
2D09	Uranium	2.0	3.0	5.0	0.600
2D24	Uranium	7.9	4.7	12.6	0.373
2D22	Uranium	4.3	3.7	8.0	0.463
2D35	Uranium	2.7	2.6	5.3	0.491

A7.2.2 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 is Li-6(n,α)H-3[32].

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.

Lithium precursor concentrations in materials present in UK ILW and LLW subject to thermal neutron activation in reactors are given in Table A29. 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) with the exception of uranium where a nominal value of 1.0 ppm has been assumed

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32 Tritium is also produced in significant quantities in fuel as a ternary fission product and can be 'manufactured' by irradiation of Li-6.

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 A29 Average lithium concentrations in reactor materials

Material	Lithium concentration (ppm)
Stainless steel 304	0.63
Stainless steel 20/25/Nb	0.79
Stainless steel 18/9	0.63
Mild steel	0.63
Magnox	~0.06
Zircaloy	0.51
Nimonic	0.85
Uranium	1.0 (nominal)
UO_2 (AGR)	0.2
UO_2 (LWR)	1.0 (nominal)
Reactor graphite (Magnox)	0.06
Reactor graphite (AGR)	0.17
Fuel graphite	0.67
Sintox	1.6

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Appendix B Waste Containers

The IGD primary focus is to quantify the amount of waste destined for geological disposal. The design of disposal container for each type of waste is a principal 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.

B1 Low Heat Generating Waste Containers

B1.1 Legacy ILW and LLW waste containers

RWM'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 which RWM has standardised designs is shown in Table B1. 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 (MBWGS) box and the 500 l RS drum an SWTC with 150 mm of steel shielding will be used.

A number of the waste containers come with internal shielding:

- 500 l RS drums can have a range of thicknesses of internal lead shielding
- 2 m and 4 m boxes can have a range of thicknesses of internal concrete shielding

The properties of the full range of legacy ILW and LLW waste containers are listed in Table B2 and Table B3.

Table B1 **Legacy waste containers for which RWM has standardised designs**

Waste container	Transport container
500 l drum	SWTC with 70 mm or 285 mm of steel shielding
3 m^3 drum	
3 m^3 box (side lifting)	
3 m^3 box (corner lifting)[33]	
Miscellaneous Beta Gamma Waste store box	SWTC with 150 mm of steel shielding
500 l RS drum	
3 m^3 RS box	Transport container design to be based on that of an ISO freight container
2 m box	Waste containers are both waste and transport packages. A transport container is not required.
4 m box	
6 m^3 box	

[33] The Sellafield 3 m^3 box and the Sellafield enhanced 3 m^3 box are instances of this container type.

Table B2 **Legacy unshielded and shielded ILW and LLW waste containers in the 2016 IGD and their properties**

Waste container	Preferred Material	Payload (m^3)	Displaced Volume (m^3)	Empty weight (t)
Unshielded ILW/LLW (UILW/LLW)				
500 l drum [34]	316L Stainless Steel	0.47	0.571	0.13
Enhanced 500 l drum (pre-cast) [35]	316L Stainless Steel / Concrete	0.40	0.571	0.40
Enhanced 500 l drum (basket) [36]	316L Stainless Steel	0.47	0.571	0.13
3 m^3 box (side lifting) [34]	316L Stainless Steel	2.7	3.27	0.75
3 m^3 box (corner lifting) [34]	316L Stainless Steel	2.8	3.61	0.75
3 m^3 drum [34]	316L Stainless Steel	2.2	2.61	0.40
MBGWS box	Mild Steel	3.5	4.7	2.0
3 m^3 Sellafield box [37]	Duplex 1.4462 SS / Concrete	2.8	3.3	1.3
3 m^3 Enhanced Sellafield box [38]	Duplex 1.4462 SS / Concrete	2.3	3.3	2.6

34 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.

35 Payload defined by Magnox Ltd for B462 drums; empty weight includes 0.13 t of steel.

36 Payload is the same as for a 500 l drum.

37 Empty weight includes 0.7 t of steel.

38 Empty weight includes 1.5 t of steel.

Waste container	Preferred Material	Payload (m^3)	Displaced Volume (m^3)	Empty weight (t)
Shielded ILW/LLW (SILW/LLW)				
2 m box (0 mm concrete) [39]	316L Stainless Steel	9.5	10.2	3.0
2 m box (100 mm concrete) [39]	316L Stainless Steel / Concrete	6.9	10.2	10.0
2 m box (200 mm concrete) [39]	316L Stainless Steel / Concrete	4.9	10.2	15.0
2 m box (300 mm concrete) [39]	316L Stainless Steel / Concrete	3.4	10.2	18.5
4 m box (0 mm concrete) [40]	316L Stainless Steel	18.9	20.0	5.0
4 m box (100 mm concrete) [40]	316L Stainless Steel / Concrete	14.3	20.0	17.5
4 m box (200 mm concrete) [40]	316L Stainless Steel / Concrete	10.9	20.0	22.5
4 m box (300 mm concrete) [40]	316L Stainless Steel / Concrete	8.1	20.0	29.5
6 m^3 concrete box (SD) [37]	Reinforced Concrete / mild steel	5.76	11.9	14.0
6 m^3 concrete box (HD) [37]	Magnetite concrete / mild steel	5.76	11.9	26.0

[39] Payload and displacement volumes are for 2 m boxes with flat side panels. Payload for 2 m box (no shielding) assumes 100 mm thick capping and ullage between the waste matrix and underside of the lid. Payloads for the shielded boxes assume the thickness of the capping and ullage between the waste matrix and underside of the lid are the same as the shielded thickness of the side and base panels. The empty mass of the shielded variants includes 3 t of steel.

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

Table B3 **Robust shielded ILW waste containers in the 2016 IGD and their properties**

Waste container	Preferred Material	Payload (m^3)	Displaced Volume (m^3)	Empty weight (t)
3 m^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
500 l RS drum (20 mm Pb)	Cast Iron / lead	0.364	1.32	6.5
500 l RS drum (30 mm Pb)	Cast Iron / lead	0.335	1.32	6.85
500 l RS drum (50 mm Pb)	Cast Iron / lead	0.285	1.32	7.48
500 l RS drum (60 mm Pb)	Cast Iron / lead	0.262	1.32	7.77
500 l RS drum (80 mm Pb)	Cast Iron / lead	0.219	1.32	8.31
500 l RS drum (90 mm Pb)	Cast Iron / lead	0.20	1.32	8.55
500 l RS drum (120 mm Pb)	Cast Iron / lead	0.149	1.32	9.23

B1.2 Legacy ILW and LLW container materials

Table B4 presents the bulk materials in the waste containers for legacy ILW and LLW.

Table B4 **The materials used in the legacy unshielded and shielded ILW and LLW waste containers. Data presented include the mass (M), thickness (T) and external area (A)[41]**

Waste container type	Stainless steel			Carbon Steel			Concrete		
	M (t)	T (m)	A (m^2)	M (t)	T (m)	A (m^2)	M (t)	T (m)	A (m^2)
Unshielded ILW/LLW (UILW/LLW)									
500 l drum	0.13	0.003	4						
Enhanced 500 l drum (pre-cast)	0.13	0.005	4				0.27	0.04	4
Enhanced 500 l drum (basket)	0.13	0.005	4						
3 m^3 box (side lifting)	0.75	0.006	14.5						
3 m^3 box (corner lifting)	0.75	0.006	14.5						
3 m^3 drum	0.4	0.005	11.2						
MBGWS box				2	0.006	16.5			
3 m^3 Sellafield box	0.7	0.006	14				0.6	0.03	14
3m^3 Enhanced Sellafield box	1.5	0.014	14				1.1	0.05	14

[41] It is assumed that only the outer geometric surfaces of the container are exposed to potential corrosion. Though there may be instances when the inner surfaces are also exposed (ie with no encapsulate) these are considered to be only a small proportion of the total surface area and not a significant contributor to gas generation.

Waste container type	Stainless steel			Carbon Steel			Concrete		
	M (t)	T (m)	A (m^2)	M (t)	T (m)	A (m^2)	M (t)	T (m)	A (m^2)
Shielded ILW/LLW (SILW/LLW)									
2 m box (100 mm concrete)	3	0.006	29				7	0.1	29
4 m box (0 mm concrete)	5	0.003	48						
4 m box (100 mm concrete)	5	0.003	48				12.5	0.1	48
4 m box (200 mm concrete)	5	0.003	48				17.5	0.2	48
6 m^3 concrete box (SD)				0.7	0.0025	31	13.3	0.24	31
6 m^3 concrete box (HD)				0.7	0.0025	31	25.3	0.24	31

Table B5 **The materials used in the legacy robust shielded ILW waste containers. Data presented includes the mass (M), thickness (T) and external area (A)**

Waste container type	Cast Iron			Lead		
	M (t)	T (m)	A (m^2)	M (t)	T (m)	A (m^2)
3 m^3 RS box	18.3					
500 l RS drum (0 mm Pb)	5.73					
500 l RS drum (20 mm Pb)	5.73			0.768	0.02	
500 l RS drum (30 mm Pb)	5.73			1.12	0.03	
500 l RS drum (50 mm Pb)	5.73			1.75	0.05	
500 l RS drum (60 mm Pb)	5.73			2.04	0.06	
500 l RS drum (80 mm Pb)	5.73			2.58	0.08	
500 l RS drum (90 mm Pb)	5.73			2.82	0.09	
500 l RS drum (120 mm Pb)	5.73			3.5	0.12	

B1.3 New Build ILW waste containers

Based on PWR operational experience in France, it is envisaged that operational ILW from a UK EPR will be packaged in reinforced 500 l and 1 m^3 concrete drums. There is no capping grout associated with the 500 l and 1 m^3 concrete drums. Proposals for the packaging of decommissioning ILW are based on the use of larger waste containers consistent with the 3 m^3 box (side lifting) and 4 m box (100 mm concrete).

The GDA report for the AP1000 states that operational ILW will be packaged in 3 m^3 boxes (side lifting) and 3 m^3 drums. Decommissioning ILW will be packaged in 3 m^3 boxes (side lifting). The properties of the packages used for new build ILW are shown in Table B6.

Table B6 **New Build waste containers in the 2016 IGD and their properties**

Waste container	Preferred Material	Payload (m^3)	Displaced Volume (m^3)	Empty weight (t)
New build UILW				
3 m^3 box (side lifting) [34]	316L Stainless Steel	2.7	3.27	0.75
3 m^3 drum [34]	316L Stainless Steel	2.2	2.61	0.40
New build SILW				
4 m box [40] (100 mm concrete)	316L Stainless Steel / Concrete	14.3	20.0	17.5
1 m^3 concrete drum (0 mm steel)	Concrete / Mild Steel	0.883	2.00	2.65
1 m^3 concrete drum (40 mm steel)	Concrete / Mild Steel	0.621	2.00	4.06
1 m^3 concrete drum (70 mm steel)	Concrete / Mild Steel	0.509	2.00	4.94
500 l concrete drum (40 mm steel)	Concrete / Mild Steel	0.291	1.24	2.75

B1.4 New Build ILW container materials

The materials used for new build ILW waste containers are shown in Table B7.

Table B7 **The materials used in the New build ILW waste containers. Data presented includes the mass (M), thickness (T) and external area (A)**

Waste container type	Stainless steel			Carbon Steel			Concrete		
	M (t)	T (m)	A (m^2)	M (t)	T (m)	A (m^2)	M (t)	T (m)	A (m^2)
New build UILW									
3 m^3 box (side lifting)	0.75	0.006	14.5						
3 m^3 drum	0.4	0.005	11.2						
New build SILW									
4 m box (100 mm concrete)	5	0.003	48				12.5	0.1	48
1 m^3 concrete drum (0 mm steel)				0.158			2.49		
1 m^3 concrete drum (40 mm steel)				1.57			2.49		
1 m^3 concrete drum (70 mm steel)				2.45			2.49		
500 l concrete drum (40 mm steel)				0.989			1.76		

B1.5 DNLEU

The packaging assumptions for MDU and depleted uranium tails (based on the preferred options identified by RWM's uranium integrated project team [B1] are that:

- The current / planned wasteform for storage would be used for disposal (ie unencapsulated UO_3 and U_3O_8 powders).
- The powders would not be repackaged, ie they will remain in their current / planned storage containers[42]:
    - depleted uranium tails (which will be deconverted from UF_6 to U_3O_8 powder in the Tails Management Facility at Capenhurst) in mild steel DV-70s.
    - older MDU (UO_3 powder) in mild steel 200 l drums that have been overpacked in large (approximately 500 l) stainless steel drums.
    - more recent MDU (UO_3 powder) in 210 l stainless steel drums.
- The current / planned storage containers would be disposed of in a stainless steel transport and disposal container (TDC), which is a 20-foot IP-2 rated 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 ~500 l drums for older MDU.
    - 2.1 m high and containing fifty-four 210 l drums for more recent MDU.
- The TDCs would be infilled with a (3:1) mixture of BFS / PFA:OPC grout prior to disposal.

The wasteform and packaging assumptions for the remaining DNLEU are the same as the assumptions for all DNLEU in the 2007 and 2010 IGDs. These assumptions apply to the wasteform and packages for Thorp Product Uranium (TPU) and depleted uranium from defence operations and miscellaneous DNLEU. It is assumed that the wasteform is in the chemical form of U_3O_8 and is mixed with a PFA / OPC encapsulant and packaged in a 500 l drum. Table B8 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 B9 to Table B11.

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[42] There is a degree of uncertainty in the future packaging of uranium. RWM has currently assumed that the quantity of uranium per container is at the lower end of the possible range. These packaging assumptions are not optimised and may be revised in a future inventory.

Table B8 **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 of 0.47 m^3, displacement volume of 0.57 m^3 and a 2 t mass limit

Table B9 **Properties of the TDC for MDU (current stocks)**

Item	Mass (t)	Material composition	Notes
UO_3 (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 of 21.92 m^3, displacement volume of 29.08 m^3

Table B10 **Properties of the TDC for MDU (future arisings)**

Item	Mass (t)	Material composition	Notes
UO_3 (equivalent mass of U)	38.9 (32.4)	UO_3	Density of UO_3 is 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)	2.40		Assuming 29% water content of grout.
TDC	6.5		
Total	54.9		Payload volume of 18.79 m^3, displacement volume of 25.44m^3

Table B11 **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 is 4.0 t/m^3
DV70 containers	3	Mild steel	4 DV70s 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 of 19.84 m^3, displacement volume of 27.87m^3

B1.6 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 RWM's inventory database software, which is then used to generate package dose rates, heat outputs, A_2 values, 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 (eg 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 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 B12. If these limits are exceeded by greater than 25% on 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 2 m box or 4 m 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 B12 **Waste package dose rate and heat output limits applied in verification of container allocations**

<table>
<tr><th>Package[43]</th><th>Heat output limit at transport</th><th>Dose rate limit[44]</th></tr>
<tr><td>500 l drum [B2] (standard or enhanced)</td><td>100 W per drum</td><td>1 m outside surface of SWTC containing 4 drums = 0.1 mSv hr^{-1}
0 m from surface of SWTC containing 4 drums = 2 mSv hr^{-1}</td></tr>
<tr><td>3 m^3 box (side lifting) [B3]
3 m^3 box (corner lifting) [B4
3 m^3 drum [B5]
MBGWS box [B6]</td><td>400 W</td><td>1 m outside surface of SWTC containing 1 box = 0.1 mSv hr^{-1}
0 m from surface of SWTC containing 1 box = 2 mSv hr^{-1}</td></tr>
<tr><td>4 m box [B7]</td><td>200 W</td><td rowspan="2">1 m outside surface of box = 0.1 mSv hr^{-1}
0 m from surface of box = 2 mSv hr^{-1}</td></tr>
<tr><td>2 m box [B8]</td><td>60 W</td></tr>
</table>

43 If multiple units are handled in an overpack then there may be a more constraining limit.

44 The dose rates shown are the dose rates against which the waste packages were reviewed in the 2013 IGD, which assumed that transport would take place under the conditions of non-exclusive use. However, since this work was carried out, use of the dose rate limits appropriate to exclusive use of a transport consignment have been approved through RWM's change management process. This changes the dose rate limits: the 0.1 mSv hr^{-1} limit applies at 2 m from the surface of the transport container rather than 1 m from the transport container; and the dose rate limit on the surface of the transport container increases from 2 mSv hr^{-1} to 10 mSv hr^{-1}. The limits used in this work are conservative.

Package[43]	Heat output limit at transport	Dose rate limit[44]
6 m^3 concrete box [B9]		3 m outside unshielded waste = 10 mSv hr^{-1}
500 l RS drum [B10]	400 W	
3 m^3 RS box [B11] 500 l concrete drum [B12] 1 m^3 concrete drum [B13]	No information available	

B2 High Heat Generating Waste Containers

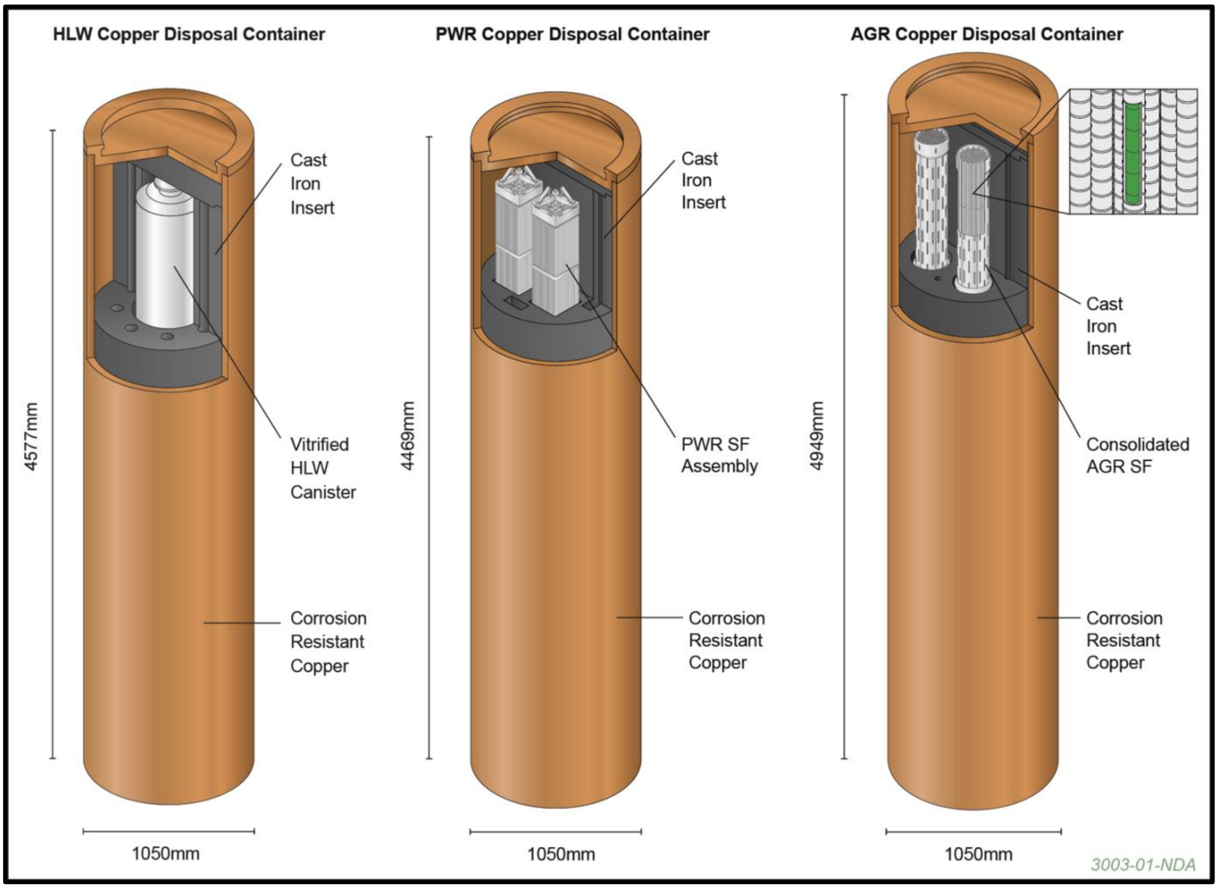
B2.1 Containers for SFs, HLW, plutonium and highly enriched uranium

RWM has two variant designs of the disposal containers for AGR SF, legacy PWR SF and HLW [B14]:

- Variant 1: a long lived disposal container designed for a higher strength host rock and based on SKB's copper / cast iron KBS-3 disposal canister concept [B15].
- Variant 2: a short lived disposal container designed for a lower strength sedimentary host rock and based on NAGRA's mild steel disposal canister concept [B16].

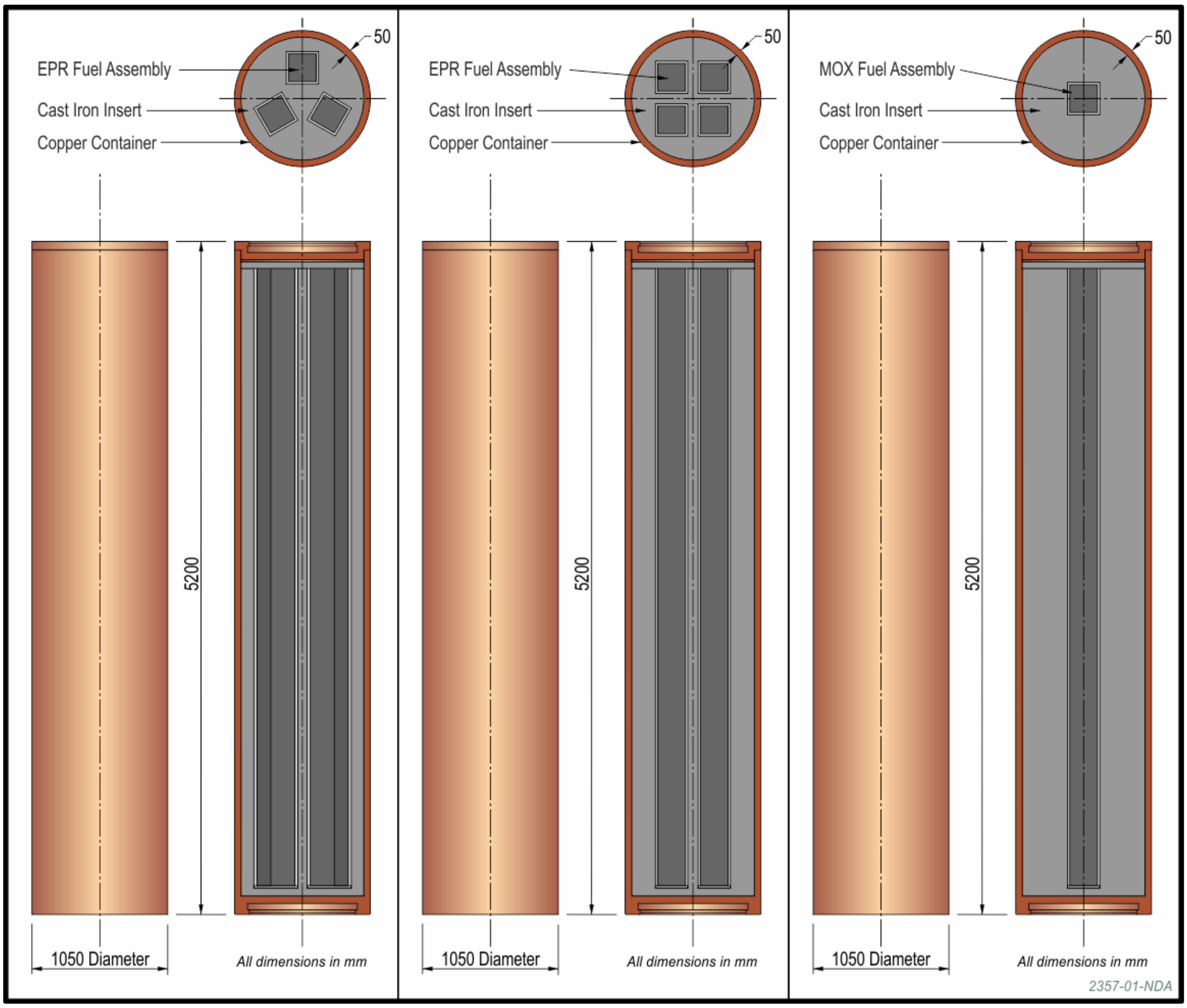
For the purposes of quantifying a single inventory for disposal, it is assumed that the Variant 1 disposal container is used. Since the packages are similar in terms of dimensions, the only IGD parameters that would change significantly if Variant 2 disposal canisters were assumed to be used are the material masses and elemental compositions.

Figure B1 **Drawings of the disposal containers for HLW, Legacy PWR SF and AGR SF**



HLW is conditioned by immobilising it in glass (vitrification) in stainless steel waste vitrification plant (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 B1 shows the disposal containers for HLW, AGR SF and PWR SF.

Figure B2 **Disposal containers for the new build and MOX SFs**



It is assumed that other SFs would also be disposed of in similar disposal containers. The new build programme is assumed to consist of only UK EPR and AP1000 reactors and the fuel assemblies for these reactors have very similar dimensions[45]. It is assumed that a single disposal container design will be used for both types of SF 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 would be possible to dispose of four in a single disposal container. Illustrations for both are presented in Figure B2.

MOX fuel assemblies are assumed to have similar dimensions to the UK EPR and AP1000 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 B2).

Although the Sellafield legacy ponds (metallic) fuels are likely to comprise various fuel types from a number of sources, the majority are likely to be Magnox reactor fuel. It is

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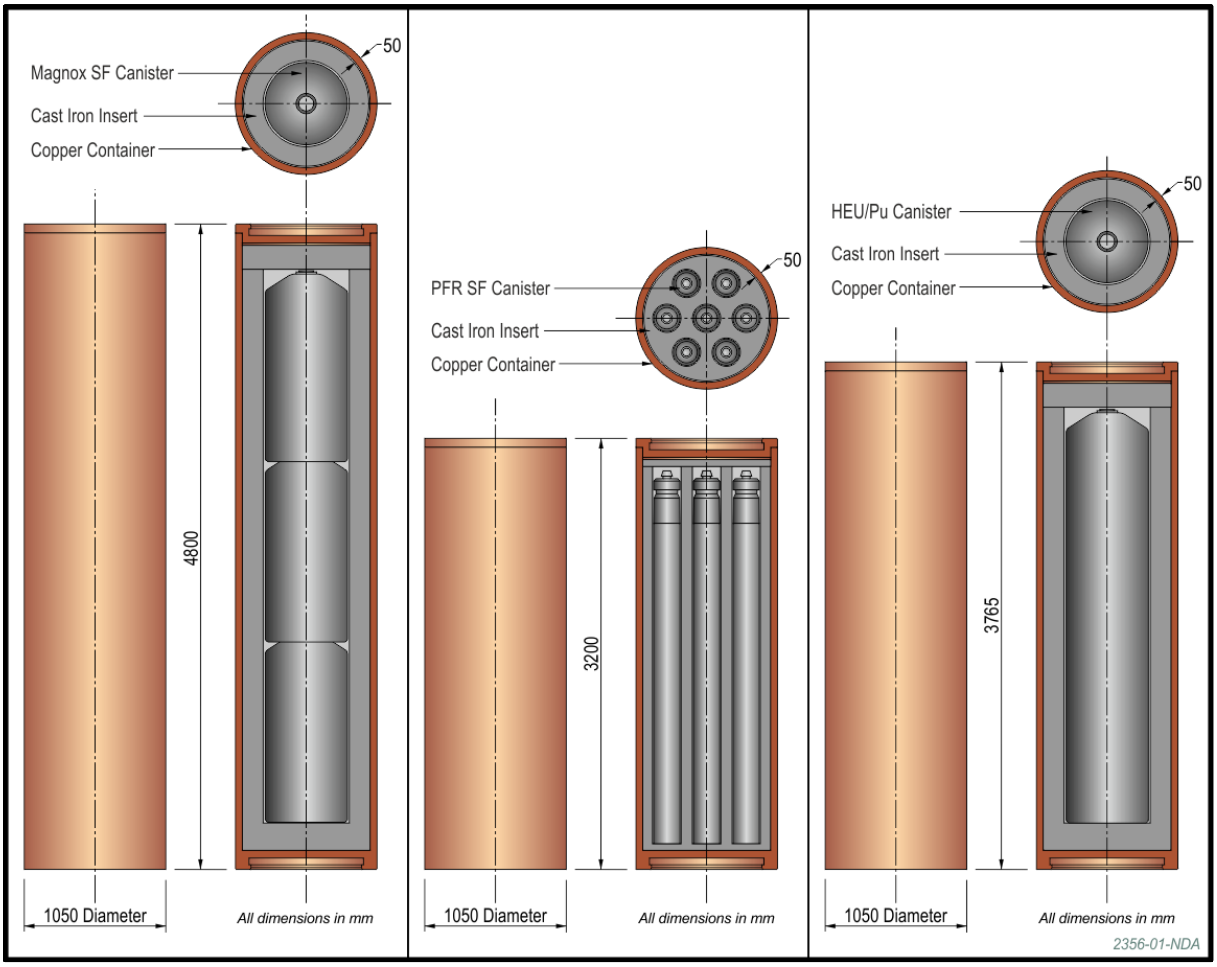
45 Both UK EPR and AP1000 fuel assemblies have the same cross sectional area as (and are about 700 mm longer than) Sizewell B fuel assemblies.

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 B3.

It is assumed that seven exotic (PFR) SF assemblies are disposed of in a single disposal container, as shown in Figure B3.

Figure B3 **Disposal containers for metallic (Magnox legacy ponds) fuels, Exotic SF and Pu / HEU**



The can-in-canister concept (see Appendix C2) is assumed for HEU and residual plutonium (that 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 B3.

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

B2.1.1 Package materials data

The materials used in the disposal containers are shown in Table B13 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 B2 and Figure B3. The material masses have been calculated for the disposal containers assuming the density of copper to be 8.90 t/m^3, the density of cast iron to be 7.20 t/m^3 and the density of carbon steel to be 7.85 t/m^3.

Table B13 **The materials used in the disposal containers**

Disposal container	Payload (m^3)	Package volume (m^3)[46]	Copper mass (t)	Cast iron mass (t)	Carbon steel mass (t)	Total mass (t)
HLW	0.583	3.87	7.41	15.8	1.06	24.2
AGR SF	0.885	4.19	7.93	16.7	0.25	24.9
PWR SF	0.744	3.78	7.26	14.3	0.25	21.8
Magnox SF	1.20	4.06	7.66	14.1	0.00	21.7
PFR SF	0.597	2.68	5.43	9.96	0.00	15.4
MOX SF	0.220	4.41	8.23	23.3	0.00	31.6
3 assembly new build SF	0.659	4.41	8.23	19.9	0.00	28.1
4 assembly new build SF	0.878	4.41	8.23	18.1	0.00	26.4
HEU / Pu	0.890	3.17	6.22	11.1	0.00	17.3

The material grades assumed for the disposal containers are based on those chosen by SKB [B15] and Posiva [B17]. The grade of copper is an oxygen-free, high conductivity grade deliberately alloyed with a small amount of phosphorus (30 – 100 ppm) to improve creep ductility in the anticipated service temperature range. The material is described by EN1976:1988 for the grades of Cu-OFE or Cu-OF1 with the additional requirements of: O < 5 ppm; P 30 – 100 ppm; H < 0.6 ppm; and S < 8 ppm. For the inserts, cast iron grade EN-GJS-400-15U has been chosen with some composition restrictions introduced to reduce the risk of radiation embrittlement. Steel guide tubes were cast integrally with the iron insert to provide an accurate guide for the SF structure and these were made from tubular hot finished hollow section steel to EN10210-1 [B18].

A number of assumptions have had to be made regarding the can-in-canister concept for Pu / HEU, for information on the canisters and titanate conditioning matrix see Appendix C2.

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

Appendix B References

B1 Radioactive Waste Management, *Geological Disposal: Investigating the Implications of Managing Depleted, Natural and Low Enriched Uranium through Geological Disposal*, NDA/RWM/142, 2016

B2 Radioactive Waste Management, *Geological Disposal: Waste Package Specification for 500 litre drum waste packages*, WPSGD No. WPS/300/03,

B3 Radioactive Waste Management, *Geological Disposal: Waste Package Specification for side-lifting variants of the 3 cubic metre box waste package*, WPSGD No. WPS/310/04, 2013.

B4 Radioactive Waste Management, *Geological Disposal: Waste package Specification for corner-lifting variants of 3 cubic metre box waste package*, WPSGD No. WPS/315/03, 2013.

B5 Radioactive Waste Management, *Geological Disposal: Waste Package Specification for 3 cubic metre drum waste packages*, WPSGD No. WPS/320/04, 2013.

B6 Radioactive Waste Management, *Geological Disposal: Specification for Miscellaneous Beta Gamma Waste Store box waste packages*, WPS/340/01, 2014.

B7 Radioactive Waste Management, *Geological Disposal: Waste Package Specification for 4 metre box waste packages*, WPSGD No. WPS/330/03, 2013.

B8 Radioactive Waste Management, *Geological Disposal: Waste Package Specification for 2 metre box waste packages*, WPSGD No. WPS/350/03, 2013.

B9 Radioactive Waste Management, *Geological Disposal: Waste Package Specification for 6 cubic metre cocrete box waste packages*, WPSGD No. WPS/360/01, 2013.

B10 Radioactive Waste Management, *Geological Disposal: Waste Package Specification for 500 litre robust shielded drum waste packages to be transported in a SWTC-150*, WPSGD No. WPS/380/01, 2015.

B11 Radioactive Waste Management, *Geological Disposal: Waste Package Specification for 3 cubic metre robust shielded box waste packages for transport as part of a Type IP-2 package*, WPSGD No. WPS/381/01, 2015.

B12 Radioactive Waste Management, *Geological Disposal: Waste Package Specification for 500 litre concrete drum waste packages*, WPSGD No. WPS/361/01, 2014.

B13 Radioactive Waste Management, *Geological Disposal: Waste Package Specification for 1 cubic metre concrete drum waste packages*, WPSGD No. WPS/362/01, 2014.

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Appendix C Conditioning and capping materials

There are no conditioning or capping materials associated with legacy SFs, MOX SF, new build SFs, HLW, or with RSCs. Appendix B reports the canisters and containers these wastes are disposed in.

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

C1 Legacy ILW and LLW

C1.1 Legacy 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.

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 RWI 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 volume (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 (ie OPC, BFS / PFA) as reported in the UK RWI. 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
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 grout are determined using the waste stream volume uncertainty factors reported in the UK RWI.
9. Waste streams packaged in 500 l RS drums and 3 m^3 RS boxes have no conditioning matrix.

C1.2 Legacy 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 (eg for sludge wastes).

Capping grout is not reported for waste streams in the UK RWI 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 (based on those used in previous IGDs (see Table C1)).

The volume and mass of capping grout for each container are given in Table C2. 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 C1 **Composition of materials used in waste conditioning grout**

Waste container type	**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 C2 **Volumes and masses of capping grout for waste containers**

Waste container type	Capping grout		
	Volume (m^3)	Mass (t)	Type
UILW			
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			
2 m box (0 mm concrete)	$4.25\ 10^{-1}$	2.47	Iron-shot concrete
2 m box (100 mm concrete)	$3.46\ 10^{-1}$	2.01	Iron-shot concrete
2 m box (200 mm concrete)	$5.50\ 10^{-1}$	3.19	Iron-shot concrete
2 m box (300 mm concrete)	$6.36\ 10^{-1}$	3.69	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
4 m box (300 mm concrete)	1.68	9.77	Iron-shot concrete

C1.3 New build ILW conditioning materials

The quantity of conditioning matrix for each new build ILW stream has been calculated from the number of packages and raw waste volume for each stream reported in the GDA disposability assessment documents for the UK EPR and AP1000 reactors [C1, C2]. The choice of conditioning matrix has been based on GDA submissions from the potential reactor operator; this results in the assumption that all new build ILW streams are to be encapsulated in cementitious grout, except for EP01 Ion Exchange Resin which is assumed to be encapsulated in a polymer conditioning matrix.

The composition of the cementitious grout is all assumed to be of 3:1 BFS/PFA to OPC mix, with the same water content and elemental composition as that for legacy ILW.

C1.4 New build ILW capping materials

Only new build ILW waste streams packaged in 3 m^3 box, drums and 4 m boxes contain capping materials, data for the amount of capping material per package can be found in Table C1.

C2 HEU and Plutonium conditioning materials

A number of assumptions have had to be made regarding the disposal concept for Pu / HEU. Neither material is currently declared as waste, they are however included in the IGD as specified by the 2014 Implementing Geological Disposal White paper (see Section 2). 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 [C3]. 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 C3.

About 20 pucks would be loaded into stainless steel cans, each 7.6 cm in diameter and 51 cm in length. Multiple cans of pucks (up to 28) would 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 a number of assumptions have been made for material characteristics and in the calculation of materials masses (see Table C3). The dimensions of the steel canister are such that a single canister would be loaded in a copper disposal canister. There is no design information for such a copper disposal canister, hence a number of assumptions have been made to derive nominal volumes and masses for materials. Table C4 gives the results of calculations for a single copper disposal canister.

Table C3 **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 C4 **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 UO_2 / PuO_2: 3.33 10^{-2} 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 C References

C1 NDA, *Generic Design Assessment: Disposability Assessment for Wastes and Spent Fuel arising from Operation of the UK EPR – Part 1: Main Report*, NDA/10747397 Issue 2, 2010.

C2 NDA, *Generic Design Assessment: Disposability Assessment for Wastes and Spent Fuel arising from Operation of the Westinghouse Advanced Passive Pressurised Water Reactor (AP1000)– Part 1: Main Report*, NDA/10897959 Issue 2, 2010

C3 D.T. Rankin & T.H Gould, Jr. *Plutonium Immobilization Program: Can-In-Canister*. WSRC-MS-99-00349, 1999.

Certificate No LRQ 4008580

Radioactive Waste Management Limited
Building 587
Curie Avenue
Harwell Oxford
Didcot
Oxfordshire OX11 0RH

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