Radioactive Waste Management

NDA Report no. DSSC/457/01

Geological Disposal

Waste Package Accident Performance Status Report

December 2016

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Abstract

The Waste Package Accident Performance status report is part of a suite of eight research status reports. The purpose of the research status reports is to describe the science and technology underpinning geological disposal of UK higher activity wastes by providing a structured review and summary of relevant published scientific literature and discussing its relevance in the UK context. The reports have been written for an audience with a scientific or technical background and with some knowledge of the context of geological disposal. The current suite of research status reports (issue 2) updates and replaces the suite produced in 2010 (issue 1).

The objective of the Waste Package Accident Performance status Report is to summarise the scientific evidence relative to our understanding of how waste packages provide the necessary physical and chemical robustness against fires and impact accidents to support the transport and operational safety cases. The key message emerging from the analysis presented in this status report is that durable waste packages, able to withstand the requirements of transport and GDF operations, and providing sound performance in potential accident conditions, have been produced or can be produced in the future for the wastes considered in the inventory for disposal.

Executive Summary

The Waste Package Accident Performance status report is part of a suite of research status reports describing the science and technology underpinning geological disposal of UK higher activity wastes.

The report provides a summary of the current understanding of the performance of waste packages under accident conditions. It also provides a review of the physical tests and computer modelling of waste package performance used to derive data for use in undertaking Disposability Assessments of waste package transport and handling operations related to the GDF.

During normal operations, including the minor operational mishaps that could occur when transporting and handling waste packages at the GDF, the waste package must provide containment for the radioactive waste with any release following an accident being minimised and progressive with accident severity, whilst avoiding cliff edges in performance. These performance characteristics are provided by the specification of high-integrity waste containers. The other key characteristic required during normal operations is the provision and maintenance of shielding against radiation. This is provided by a combination of the transport container, the waste container, the wasteform and other elements of the transport and handling systems.

In the event of a more significant accident occurring during transport and handling, or during emplacement, the waste package must prevent where possible, or otherwise minimise, the release of radioactivity. Once again, the high-integrity waste container will serve to prevent release in most credible accidents. However, for packages where a waste container breach is foreseeable, the wasteform is typically designed to retain as much of the waste as possible for as long as possible. There are exceptions to this, such as Depleted, Natural and Low Enriched Uranium, where the raw waste presents a lesser hazard and for example, a powder may be acceptable.

We have identified a number of features that can be included in waste package designs to ensure that all risks associated with the waste packages are as low as reasonably achievable. These include features which contribute to maintaining normal operations (such as standardised lifting / handling features), features which will prevent or minimise immediate releases (for example, high-integrity waste containers) and features which will minimise longer term impacts (such as the immobilisation of particulate material to minimise release from a breached waste container where this is a reasonably foreseeable scenario).

We work with waste packagers to develop a range of measures that can be applied to the design of waste packages to provide safe performance in accident conditions, such as the choice of wasteform encapsulant, specification of waste container materials and additional internal waste package features to absorb impact energy or provide thermal shielding. Under the Disposability Assessment process individual waste package designs are systematically reviewed, including a detailed consideration of impact and fire performance.

Where the waste package is transported in a reusable transport container, it will provide additional containment to the release of radioactive material and hence further reduce the quantity of radioactive material potentially coming into contact with workers and members of the public.

The UK nuclear industry has over 60 years of experience in safely managing radioactive wastes. This includes safely conditioning, packaging, storing, handling and transporting waste packages. Accidents involving waste packages are rare and accidents that compromise the performance of a waste package and its ability to provide the necessary level of protection are extremely rare. Nevertheless, the research and development summarised in this report is primarily concerned with underpinning the performance of waste packages in accident conditions.

The GDF will receive and emplace tens of thousands of waste packages. It is recognised that, even incorporating all feasible measures to reduce the possibility of accidents, there is still a possibility that they may occur. In order to minimise the consequences of these accidents we have defined a number of scenarios and have included design features to address these. The possible accident conditions that we consider are:

- impact accidents (for example, a dropped load during handling)
- fire accidents (for example, during GDF emplacement)
- combined impact and fire accident (for example, a vehicle crash followed by a fuel fire).

The performance of waste packages in simulated accident conditions has been reviewed in this report confirming the effectiveness of the design features in providing the required performance characteristics.

Waste packages perform both predictably and progressively in physical testing and have given us a high level of confidence in their performance in the unlikely event of a significant accident. This is based on a large number of physical tests of a variety of waste containers and wasteforms supplemented by detailed numerical analyses using validated computer models. The physical tests are used to validate the numerical analyses, which are used subsequently to assess additional scenarios. Over 50 drop tests have been carried out on 500 litre drums, with fewer tests on the larger waste packages. Full-scale fire tests were performed on a small number of waste packages containing simulated inactive waste, confirming the integrity of the waste packages in fire accident conditions. This understanding of impact and fire waste package accident performance has been improved with computer simulation modelling and small-scale tests.

In assessing the performance of waste packages, particularly for accidents involving impacts or fires, a number of waste container-specific Release Fractions (RFs) have been derived. These RFs are suitable for use in undertaking conceptual stage safety assessments.

This report shows how we have developed our understanding of our disposal concepts with regard to waste package performance. Experimental testing and mathematical modelling will continue to extend our knowledge and understanding. This in turn will help to develop our disposal concepts and to refine our waste packaging advice. We identify a number of areas where RF values could be refined or where other work would provide a better understanding of the behaviour and performance of waste packages in accident conditions. These knowledge gaps will be addressed through the research and development activities documented in our science and technology plan.

List of Contents

List of acronyms

AGR	Advanced Gas-cooled Reactor
DNLEU	Depleted, Natural and Low-Enriched Uranium
DSS	Disposal System Specification
DSSC	Disposal System Safety Case
DU	Depleted Uranium
EC	European Commission
ESC	Environmental Safety Case
FEA	Finite Element Analysis
GDF	Geological Disposal Facility
GWPS	Generic Waste Packaging Specification
HEU	High-Enriched Uranium
HHGW	High Heat Generating Waste
HLW	High Level Waste
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
LHGW	Low Heat Generating Waste
LLW	Low Level Waste
LoC	Letter of Compliance
LoD	Limit of Detection
MBGWS	Miscellaneous Beta Gamma Waste Store
MWB	Multiple Water Barrier
OPC	Ordinary Portland Cement
OSC	Operational Safety Case
PDSR	Package Design Safety Report
PFA	Pulverised Fly Ash
PSA	Probabilistic Safety Assessment
PWR	Pressurised Water Reactor
RF	Release Fraction
RSC	Robust Shielded Container
SF	Spent Fuel
SILW	Shielded Intermediate Level Waste
SWTC	Standard Waste Transport Container
TSC	Transport Safety Case
UILW	Unshielded Intermediate Level Waste
UK RWI	United Kingdom Radioactive Waste Inventory

WAGR	Windscale Advanced Gas-cooled Reactor
WPS	Waste Product specification
WVP	Waste Vitrification Plant

1 Introduction

1.1 Background

In order to build confidence in the safety of a future geological disposal facility (GDF) for the UK[1], in the absence of potential disposal sites, RWM is developing a generic Disposal System Safety Case (DSSC), which shows how the waste inventory destined for geological disposal could be safely disposed of in a range of geological environments. Background information on geological disposal in the UK can be found in the Technical Background Document [1].

The documents comprising the generic DSSC are shown in Figure 1 and include a number of research status reports ('knowledge base'). The purpose of the research status reports is to describe the science and technology underpinning geological disposal of UK higher activity wastes by providing a structured review and summary of relevant published scientific literature and discussing its relevance in the UK context. The current suite of research status reports (issue 2) updates and replaces the suite produced in 2010 (issue 1).

Figure 2 shows how research status reports underpin different safety cases. They include:

- reports on package evolution [2], engineered barrier system (EBS) evolution [3], and geosphere [4], describing the understanding of the evolution of the specific barriers of the multi-barrier system
- reports on radionuclide behaviour [5] and gas generation and migration [6], describing the release and movement of materials through the multi-barrier system, including the groundwater and any gas phase formed
- reports on criticality safety [7] and on waste package accident performance (this report), describing the behaviour of waste packages and the GDF during low probability events
- a report on the biosphere [8], describing how we think the biosphere may evolve in the future and how radionuclide uptake might be expected to take place.

Research status reports need to be read in conjunction with other documentation, including:

- the Data Report [9], which describes the values of specific parameters used in the safety assessments based on scientific information presented in the status reports
- the Science and Technology Plan [10], which describes planned research and development activities .

1.2 Objectives and scope

The objective of the Waste Package Accident Performance status report is to summarise the scientific evidence relative to our understanding of how waste packages provide the

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[1] Disposal of higher activity wastes in a GDF is current policy in England, Wales and Northern Ireland. Scottish Government policy is that the long-term management of higher activity waste should be in near-surface facilities. Facilities should be located as near to the sites where the waste is produced as possible.

necessary physical and chemical robustness against fires and impact accidents to support the transport and operational safety cases.

This report summarises physical tests and computer modelling of waste package accident performance and derives data for use when undertaking safety assessments of waste package transport and handling operations related to the GDF. This understanding has been gained through an extensive programme of research and development (R&D) activities combined with transferable information from other waste management organisations and research institutions overseas.

The scope covers all packages currently considered in the derived inventory for disposal. It covers packages from when they depart their originating site, through the GDF operational phase, including emplacement, and until GDF operations cease and the GDF is closed. That is, it does not cover package incidents within any waste producers packaging plants, interim store, or during the post closure phase of the GDF lifecycle.

Figure 1: Structure of the generic DSSC. The suite of research status reports represents the knowledge base

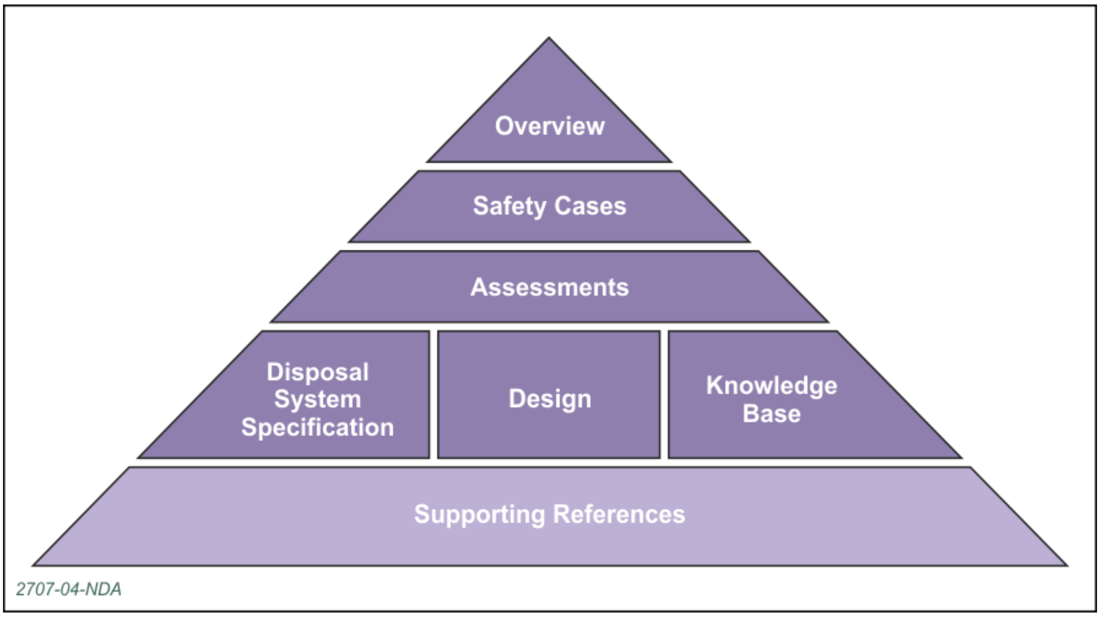
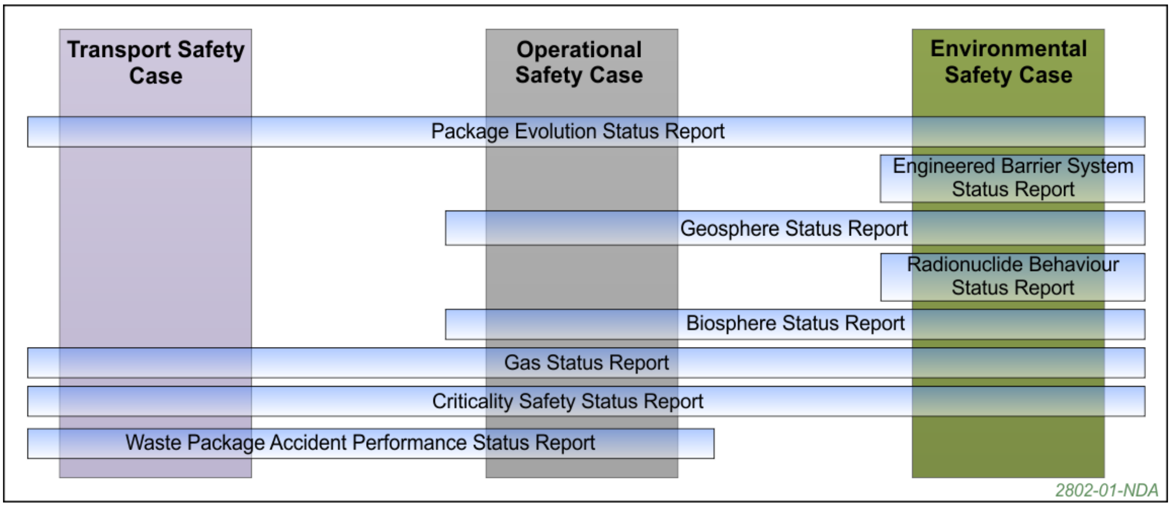


Figure 2: Safety cases and status reports in which underpinning information can be found



1.3 Audience and Users

The primary external audience of the status reports is our regulators. The audience is also expected to include academics, learned societies and stakeholders such as the Committee on Radioactive Waste Management (CoRWM) and Non-Governmental Organisations (NGOs). The reports have been written for an audience with a scientific or technical background and with some knowledge of the context of geological disposal. The primary internal user of the information presented herein is RWM's safety case team.

1.4 Relationship with other status reports

There are important interfaces between this report and the Package Evolution status report, which provides underpinning information on how waste containers and wasteforms may evolve during the storage, transport, and GDF operational and post-closure phases.

1.5 Changes from the previous issue

This document updates and replaces the 2010 Waste Package Accident Performance status report [11], published as part of the 2010 generic DSSC suite. This issue includes the following developments:

- inclusion of consideration of new package types (Robust Shielded Containers (RSCs)and concrete containers) introduced in the 2013 Derived Inventory
- information on impact modelling of packages inside a Standard Waste Transport Container (SWTC)
- further information on the disposal container for High Heat Generating Waste (HHGW)
- updated fire and impact scenario information together with a fuller description of these scenarios
- further information on the holistic impact methodology and how this is used in deriving impact fault release fractions.

In line with the objectives of the document and to respond to previous feedback, contextual and safety-related information has been removed from the text. Contextual information is provided in [1], while safety-related information is described entirely in the safety case documentation.

1.6 Knowledge base reference period

The knowledge base described in this document contains scientific information available to RWM up to March 2016. Where, within RWM's research programme, progress relative to important topics was made after such date, efforts have been made to reflect such progress up to the publication date of this document.

1.7 Terminology

For information about use of language and terminology in this and other RWM documents please refer to our Glossary [1]. When necessary, we have introduced specific terminology used in the document through the use of footnotes.

1.8 Document structure

The remainder of this report is structured according to the following format:

- section 2 provides an overview of the waste packages that we anticipate will be used for the packaging of radioactive waste for disposal in the GDF

- section 3 discusses the potential impact and fire accident scenarios that could occur during transport to and operations in the GDF, how we quantify releases and international experience of Waste Package Accident Performance
- section 4 reviews published information relating to impact damage to waste packages
- section 5 reviews published information relating to fire damage to waste packages
- section 6 provides an overview of the way the available data is used to underpin Release Fractions.

We have used coloured boxes at the beginning of each section to provide a short summary of the key messages and help the reader in following the ‘golden thread’.

2 Waste packages

In this section we describe the range of waste packages that we expect will be disposed of in the GDF and the categories of waste that are likely to be placed within them, although we recognise that future developments may lead to changes in the range of waste packages and that new waste packages will be developed in the future. We also describe how the design of the waste packages influences the options for transport to the GDF and operations to emplace the waste packages in the GDF. These choices in moving and handling waste packages have a bearing on the types of accidents that could arise in the generic disposal system, as described in Section 3. In all cases, disposal of wastes in a GDF will have to comply with the Disposal System Specification (DSS) [12].

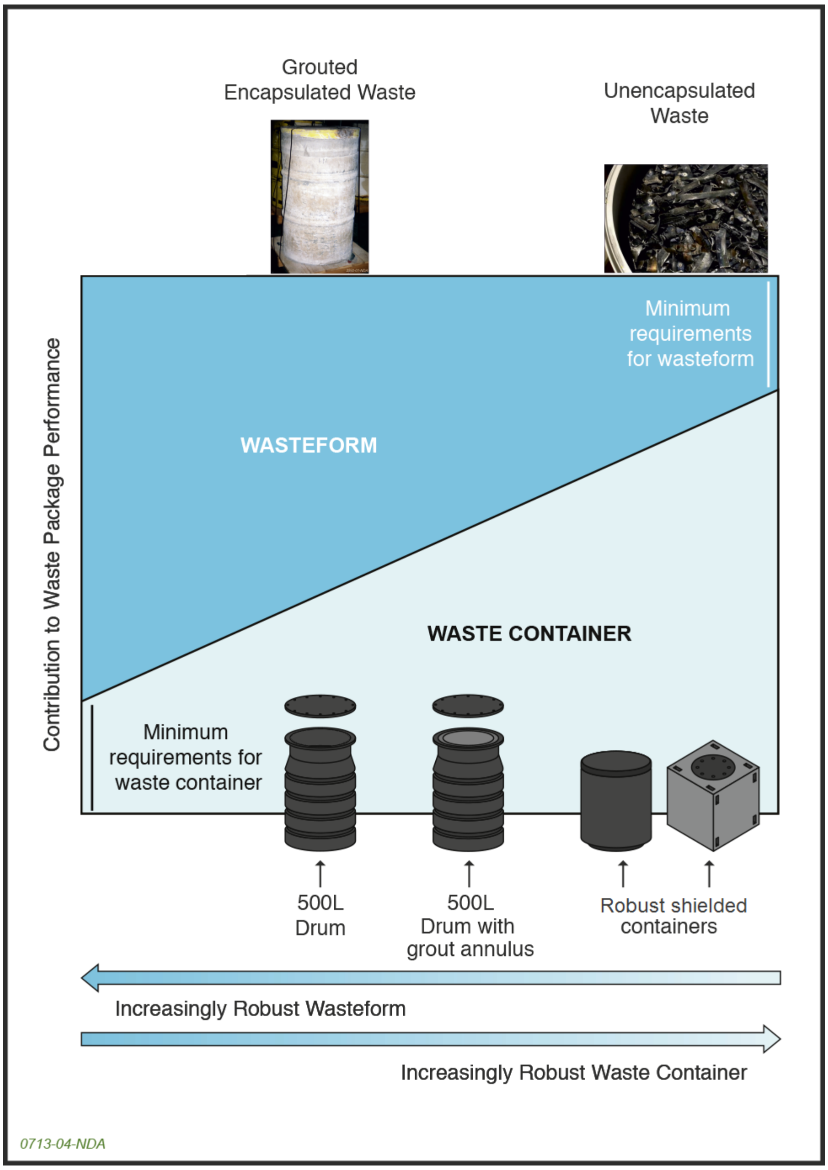
In the context of the GDF a waste package comprises the initial containment barriers (wasteform and container) to the spread of radioactivity from waste, with the performance of the package as a whole being the sum of the contributions from the two components. As one of the components becomes less robust, more reliance must be placed on the other component providing the necessary performance (see Figure 3). Whilst there is a wide range of wasteforms (for example, glass-encapsulated High Level Waste (HLW), solid Intermediate Level Waste (ILW) material bound within a cementitious grout, ion-exchange resins immobilised within epoxy resin or unencapsulated waste), there is also a well-defined range of waste container types. These waste containers in combination with the wasteforms give rise to three broad categories of waste package, these are described in the next three sub-sections:

- unshielded ILW (UILW) waste package (Section 2.1.1)
- shielded ILW (SILW)/ Low Level Waste (LLW)/RSC waste package (Section 2.1.2)
- HHGW disposal container (Section 2.2).

In developing the waste package designs that are available for use in the UK, common features have been included that facilitate the waste management process and minimise the risk of human error for example by appropriate selection of handling equipment or application of interlocks. These include aspects such as common lifting features, and compatible external dimensions and features to allow the stacking of waste packages. Working with waste packagers, we have devised a range of techniques to ensure that raw radioactive waste is immobilised to form a passively safe wasteform within a waste container (for example, a steel drum such as that shown in Figure 4 and Figure 5) with the combination of the wasteform and the waste container forming a waste package. Figure 5 shows a schematic of the components of a typical 500 litre drum and a drum with and without a grout annulus surrounding the wasteform. In the future, we will continue to work with waste packagers to develop further waste package designs to ensure that appropriate packaging options are available for all types and forms of waste identified in the inventory for disposal [13].

The International Atomic Energy Agency (IAEA) Transport Regulations [14] define a number of transport package options, two of which have been identified for radioactive waste transport. The requirements are introduced in Box 1 below, and developed further in the following three sub-sections.

Figure 3: Schematic representation of the contributions of wasteform and waste container to waste package performance



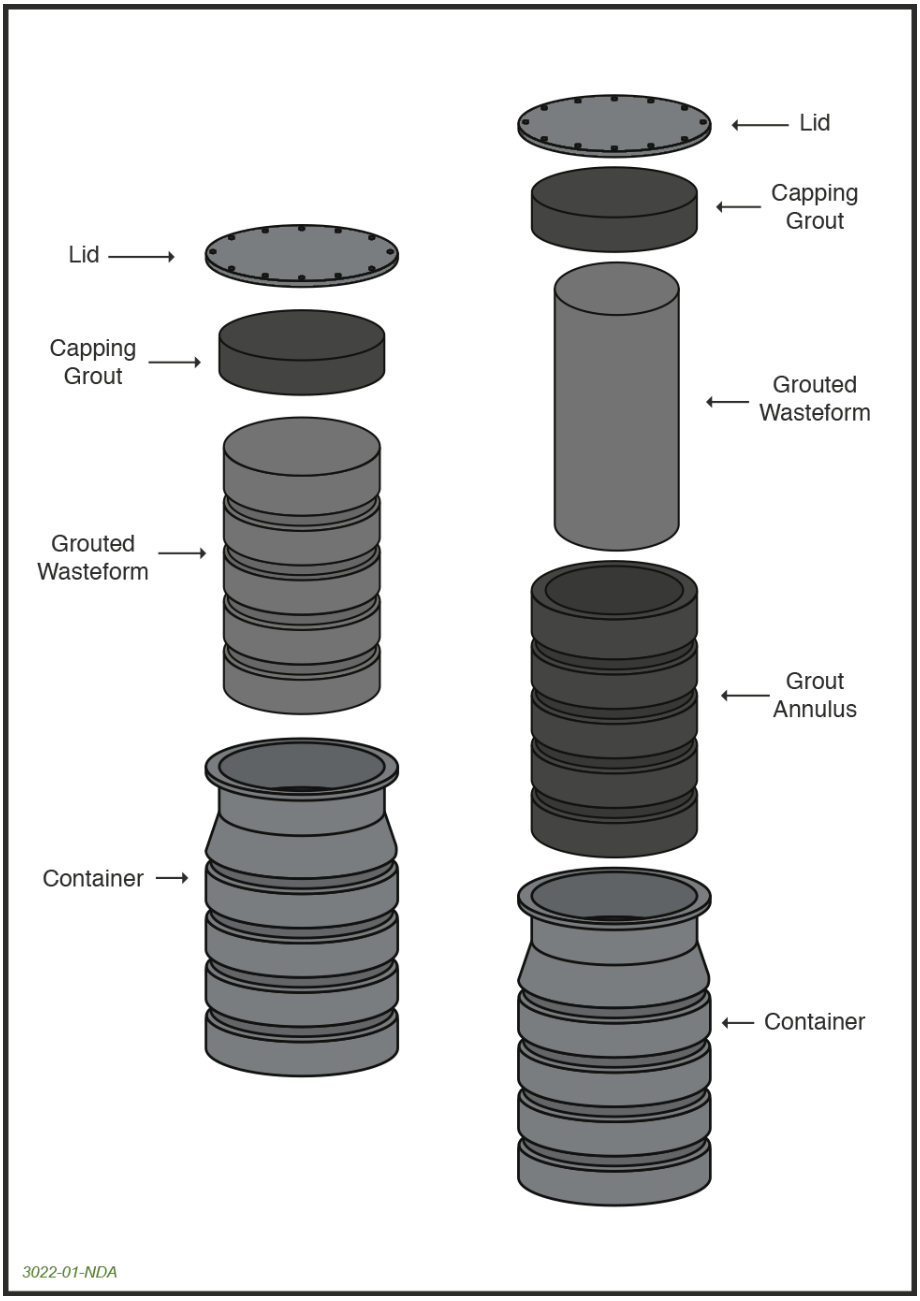
Box 1 Transport packages

Transport packages consist of all those items which constitute a package that can be transported on public highways and railways in accordance with the UK regulatory requirements, which are in turn derived from the IAEA Transport Regulations [14]. To allow waste packages to be transported, some require a separate reusable transport container, while other waste packages are suitable for transport without additional packaging. Transport containers are reusable containers that will be used to transport the waste packages. These transport containers will make multiple trips to the GDF.

Under the IAEA Transport Regulations, the allowable contents of Industrial Package (Type-IP) waste containers are limited to materials that qualify as low specific activity material and/or surface contaminated objects. Type B(U) transport containers are used for materials with a greater hazard (greater levels of activity). The use of the transport package is described in Section 2.1.1.

Figure 4: Illustration of a 500 litre drum waste package containing grouted metallic waste

Figure 5: Illustration of 500 litre drum waste packages without (left) and with (right) a grout annulus[2]



[2] A grout annulus can provide significant thermal protection of the contained wasteform; it also provides a layer of material that may crush to absorb energy imparted from impact faults and act as shielding to absorb radiation, as well as protecting the drum from corrosive degradation products.

2.1 ILW, LLW and Depleted, Natural and Low-Enriched Uranium (DNLEU)

There are several standard container types available to waste producers for ILW that conform to the General Waste Packaging Specifications for low heat generating wastes. Waste producers may also propose alternative packaging that must meet the same requirements as the standard packages.

ILW and LLW destined for geological disposal are assumed to be packaged in such a manner that will ensure compliance with the Generic Waste Packaging Specifications (GWPS) for low heat generating wastes [15]. This will generally involve the use of one of the standardised waste containers defined in Sections 2.1.1 and 2.1.2, together with a conditioning process that ensures adequate immobilisation of the radionuclides associated with the waste. Some waste may be disposed of in Robust Shielded Containers where greater reliance is placed on the container; as such these wastes may not be immobilised. Some ILW may be vitrified and placed within a container specifically designed for this purpose.

A Generic Specification for waste packages containing Depleted, Natural and Low-Enriched Uranium (DNLEU) also exists [16]. Packaging options for the disposal of DNLEU are being investigated within a multi-disciplinary uranium disposal project. This includes investigating disposal in a number of packaging options (500 litre drums, 3 cubic metre boxes, DV70 boxes, waste integrated into backfill material).

2.1.1 UILW and DNLEU waste packages

Standard unshielded ILW containers include the 500 litre drum, 3 cubic metre box, 3 cubic metre drum and the miscellaneous beta gamma waste store box. These packages require transport within a further container, known as the Standard Waste Transport Container, to ensure compliance with the IAEA Transport Regulations. The DV70 container is one possible container for DNLEU and as such is included here as an example.

Most UILW packages will need to be stored and handled in facilities that prevent direct operator access as there may be high external dose rates on these waste packages. Waste producing facilities, stores and the GDF must therefore be able to remotely handle these UILW packages.

In conjunction with waste packagers we are continuing to develop and extend the range of waste container design options for packaging waste. To date, we have identified four standard UILW packages (see Figure 6).

Options for packaging of DNLEU for final disposal are at an early stage. As part of this process, the DV70 container is being considered (Figure 7), along with other containers discussed herein:

- 500 litre drum
- 3 cubic metre box
- 3 cubic metre drum
- Miscellaneous Beta Gamma Waste Store (MBGWS) box
- DV70 box (under consideration for DNLEU only).

As far as possible, these UILW waste packages have common dimensions and handling features, which contribute to the overall safety during handling and transport. The dimensions and capacity of the UILW and DNLEU waste containers are given in Table 1 [17, 18, 19, 20].

Figure 6: Illustrations of UILW waste containers

Figure 7: Illustration of the DV70 waste container (being considered for the disposal of DNLEU)

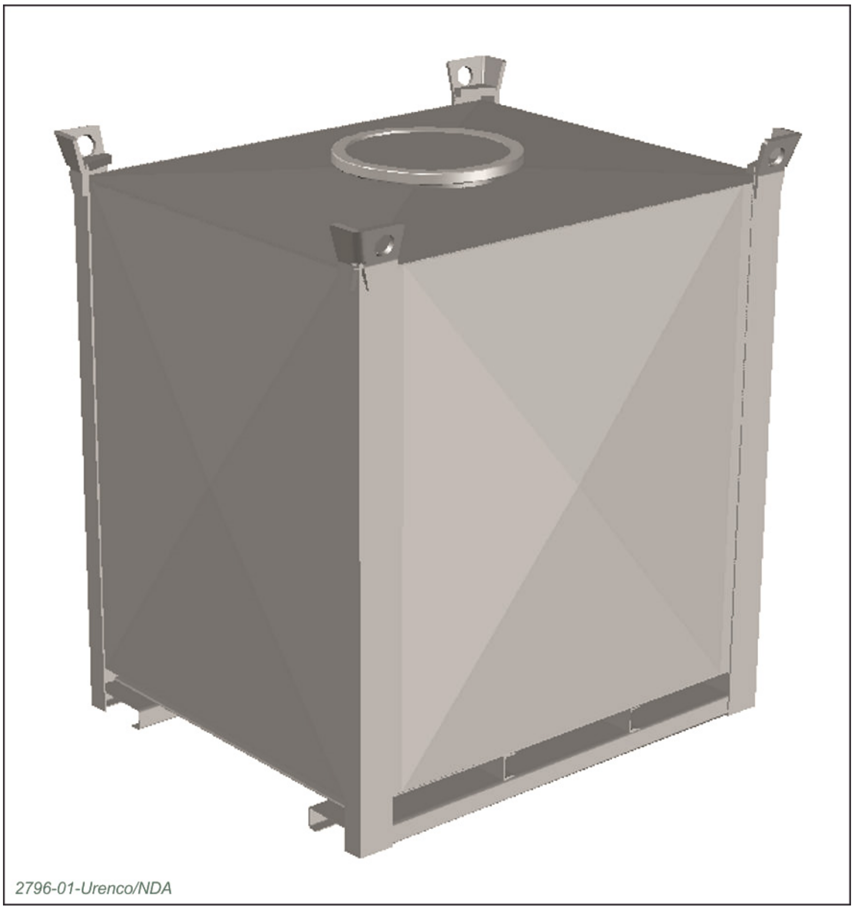


Table 1: Dimensions of the standard UILW containers and a proposed DNLEU waste container

UILW waste container	Dimensions	Maximum waste package mass	Wall construction
500 litre drum [17]	Height: 1230 mm Diameter: 800 mm	2000 kg	Stainless steel of 2.5 mm thickness. Variations with concrete annulus available.
3 cubic metre box (side and corner lifting design variants) [18]	Height: 1245 mm Plan: 1720 mm	12000 kg	Stainless steel of 6 - 8 mm thickness. Variations with inner steel liner and annulus available.
3 cubic metre drum [19]	Height: 1245 mm Diameter:1720 mm	12000 kg	Stainless steel of 5 mm thickness.
MBGWS box	Height: 1370 mm	11000 kg	Stainless steel of 10 mm

[20]	Plan: 1850 mm		thickness.
DV70 box	Height: 1880 mm Plan: 1745 x 1445 mm	12750 kg	Mild steel of 6mm thickness.

We are also working with waste packagers to develop the range of waste containers and packaging techniques for specific applications. For example:

- non-immobilisation of wastes. Until recently immobilisation using a grout or other encapsulant formulation has been the accepted approach for all ILW/LLW wastes identified for the GDF. However, for some wastes, such as reactor core graphite, there is very little benefit provided by grouting and possible cost and dose detriments.
- dried wastes. If the containment function is provided predominantly by the waste container, such as a thick-walled RSC, then there could be reduced demands on the wasteform.

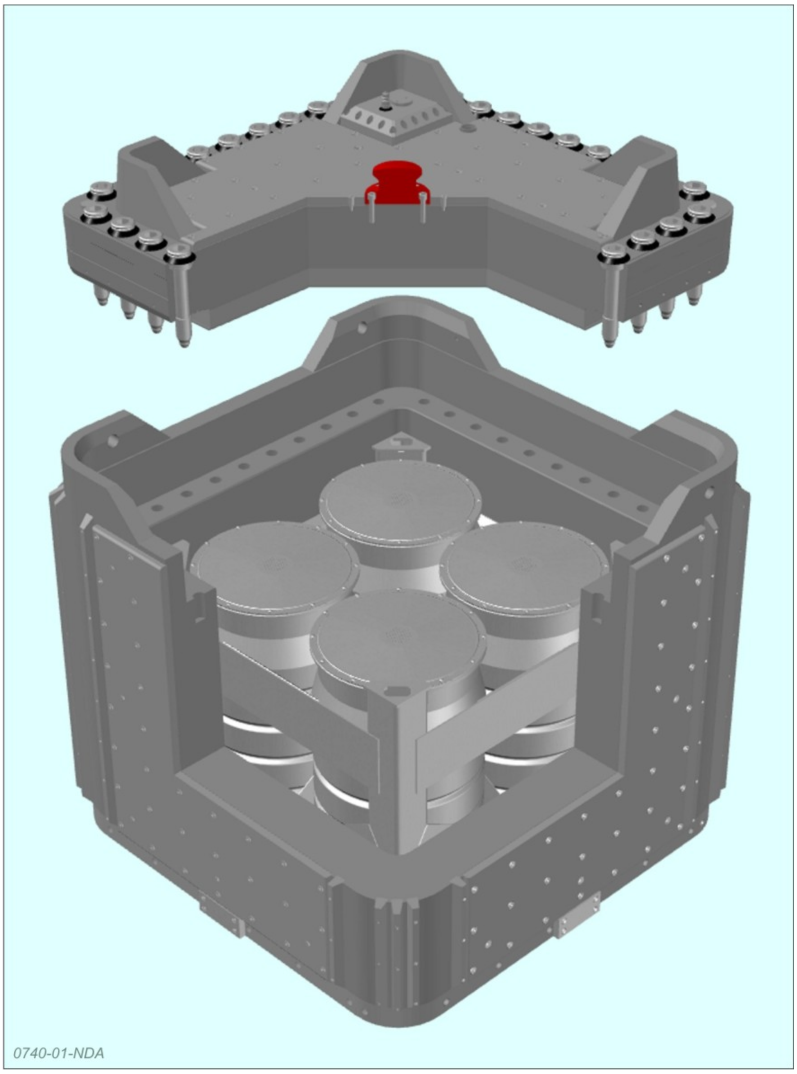
We have developed a design for a SWTC [21] to transport UILW waste packages. Together, the SWTC and the UILW package(s) provide both the radiation shielding and containment that meet the requirements for a Type B(U) transport package under the IAEA Transport Regulations. Three SWTC designs have been developed for the transport of either four 500 litre drum waste packages in a transport stillage, one 3 cubic metre box waste package, one 3 cubic metre drum or one MBGWS box waste package. The designs are differentiated largely on the basis of the thickness of the shielding provided as follows:

- SWTC with 285 mm of shielding (SWTC-285)
- SWTC with 150 mm of shielding (SWTC-150)
- SWTC with 70 mm of shielding (SWTC-70).

A SWTC-285 containing four 500 litre drums in a transport stillage is shown in Figure 8. Depending on the dose rate from the 500 litre drums, safety could be provided by one of the other lighter SWTCs.

Performance evaluation work for the 285 mm shielded SWTC has included extensive numerical modelling to demonstrate that the basis of the designs is sound. The results show that the SWTC concept will provide the basis for an acceptable full size Type B(U)F design. Further, half-size physical testing has been carried out in order to demonstrate compliance with the Type B(U)F regulatory requirements. Finite element analysis has also been carried out to examine the consequences of an impact accident involving a SWTC containing either 500 litre drums or a 3 cubic metre box (see Section 4.1).

Figure 8: Four 500 litre drums in a SWTC-285 transport container



2.1.2 SILW, LLW and RSC waste packages

Standard SILW, LLW and Robust Shielded waste Containers (RSC) include the 500 litre concrete drum, 1 cubic metre concrete drum, 2 metre box, 4 metre box, 6 cubic metre box, 500 litre robust shielded drum and the 3 cubic metre robust shielded box. These containers are designed to be self-shielding and some fulfil the requirements of the IAEA Transport Regulations as ‘industrial Packages’ without a transport container.

There are a number of SILW, LLW and RSC waste packages that are designed for use as disposal packages, some of which are designed to qualify as transport packages in their own right without the need for additional outer packaging to provide radiation shielding or containment. To ensure that the SILW/LLW packages do not need remote handling, their use is either restricted to low activity materials or they have built-in shielding to control radiation dose. These SILW/LLW packages are designed as Industrial Packages (Type-IP) under the IAEA Transport Regulations [14] and so the allowable contents of SILW/LLW packages are limited to materials that qualify as low specific activity material and/or surface contaminated objects.

In conjunction with waste packagers, we are continuing to develop and extend the range of waste container design options for packaging waste. We have currently identified a number of SILW/LLW/RSC waste packages (see Figure 9):

- 500 litre concrete drum
- 1 cubic metre concrete drum
- 2 metre box
- 4 metre box
- 6 cubic metre box
- 500 litre robust shielded drum
- 3 cubic metre robust shielded box

The SILW/LLW containers can be manufactured from steel or concrete and provided with internal shielding to control external radiation dose rates.

The Disposal System Specification (DSS) [12] gives four options ranging from no shielding through to 300 mm thick concrete shielding for the 2 metre box and 4 metre box containers. The 6 cubic metre box concrete shielding is fixed at 240 mm, but the density can be increased to enhance the effectiveness of the shielding.

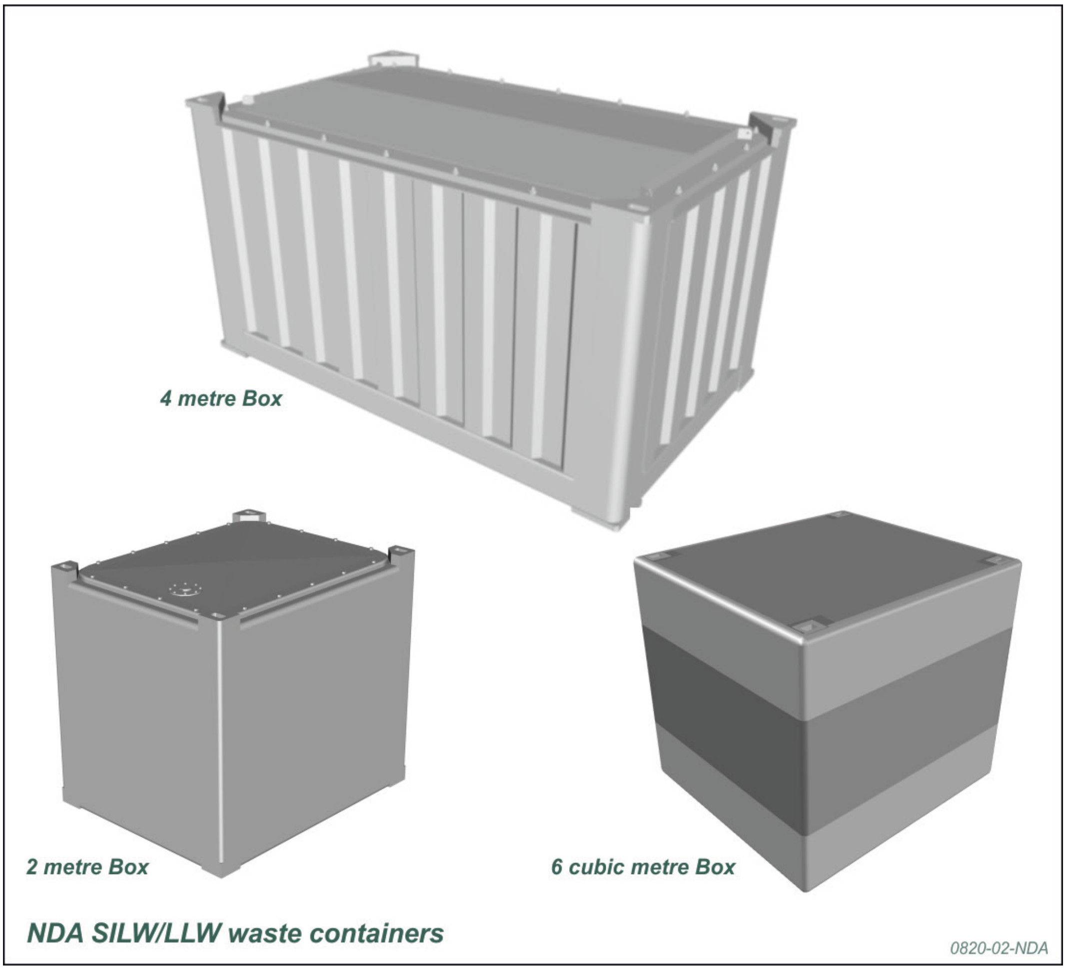
The design of these SILW/LLW packages includes eight twistlock fittings, four on the top face and four on the base, to enable lifting, restraint and handling by conventional means. We expect that these SILW/LLW packages will be used primarily for packaging wastes arising from the decommissioning of nuclear facilities. We have developed the designs of these SILW/LLW packages such that they are transportable in their own right and can be disposed of in the GDF. The dimensions and capacity of the SILW/LLW/RSC containers are given in Table 2 [20, 22, 23, 24, 25, 26].

The RSC waste packages are thick-walled containers, often with no additional shielding. The philosophy behind the development of robust shielded waste packages, such as those manufactured using cast iron, is that adequate safety is achieved as a result of the robustness of the waste container with little or no contribution from the contents of the waste package. Accordingly, waste packages manufactured using cast iron waste containers will generally contain waste which is not ‘encapsulated’ (that is, immobilised with a cementitious or polymer grout) and for which only basic conditioning has been carried out prior to packaging (such as drying or size reduction). The RSC packages are intended to be delivered to the GDF in transport containers [24, 26].

Figure 9: Illustrations of SILW/LLW/RSC waste containers

(a) 500 litre concrete drum and 1 cubic metre concrete drum

(b) 2 and 4 metre boxes and 6 cubic metre box



(c) 500 litre robust shielded drum and 3 cubic metre robust shielded box

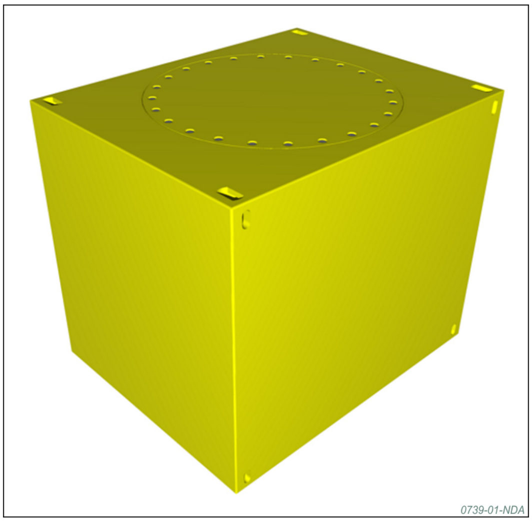


Table 2: Dimensions and capacity of the SILW/LLW/RSC waste containers

SILW/LLW waste container	Dimensions	Maximum gross waste package mass	Wall construction
500 litre concrete drum [27]	Height: 1302 mm Diameter: 1102 mm	6,000 kg	Reinforced concrete with walls of 150mm thickness.
1 cubic metre concrete drum [25]	Height: 1302 mm Diameter: 1402 mm	8,000 kg	Reinforced concrete with walls of 150mm thickness.
4 metre box [23]	Height: 2200 mm Length: 4013 mm Width: 2438 mm	65,000 kg	Stainless steel of 3 mm thickness, incorporating a concrete liner, of up to 200mm thickness.
2 metre box [22]	Height: 2200 mm Length: 1969 mm Width: 2438 mm	40,000 kg	Stainless steel of 3 mm thickness, incorporating a concrete liner, of up to 200mm thickness.
6 cubic metre box [28]	Height: 2200 mm Length: 2210 mm Width: 2438 mm	50,000 kg	Reinforced concrete with walls of 240mm thickness. A carbon steel collar is present at the top and base of 8 mm thickness.
500 litre robust shielded drum [24]	Diameter: 1070	10,000 kg	Ductile cast iron of 160mm thickness. Versions with

	mm Height: 1520 mm		further lead shielding are available.
3 cubic metre robust shielded box [26]	Length: 2010 mm Width: 1610 mm Height: 1740 mm	25,000 kg	Ductile cast iron of 150mm thickness. Versions with further lead shielding are available.

SILW/LLW packages are used for lower activity wastes than UILW packages in order to be able to comply with the transport regulatory requirements for Industrial Packages (Type-IP). These wastes are typically encapsulated within a cementitious grout to produce a solid wasteform within the waste container. The waste package therefore has a relatively low radioactive inventory and, in the unlikely event of a breach of the waste container, only a small amount of the material would be released. This ensures that the waste package is suitable for transport and emplacement in the GDF. Any exposure of a worker or member of the public would be relatively small, even under accident conditions. Non-immobilised wastes will be transported within a robust package type to prevent release or will be of low enough specific activity that doses will not challenge any safety requirements.

The 6 cubic metre boxes were designed for the packaging of specific wastes associated with the decommissioning of the Windscale AGR, but may be suitable for wider use. A number of 6 cubic metre boxes have been filled and the waste packages placed in an interim storage facility. As of 2015, Dounreay Site Restoration Ltd is updating the design of the 6 cubic metre box with revised steel re-enforcement bars and a different concrete formulation. The new design will be assessed against RWM's waste package specifications in due course and any resulting research requirements will be added to our research programme.

To date, only prototype 2 metre box or 4 metre box waste containers have been manufactured. A significant number of waste streams have been identified for packaging in these two waste container types for disposal in the GDF, mainly comprising later stage decommissioning wastes. We will continue to keep the designs under review so that we can ensure they are appropriate for the wastes that need packaging and for the developing disposal system concept design.

2.2 HLW, SF, HEU and plutonium

Current packaging assumptions are that HLW will be vitrified and spent fuel will be packaged in high-integrity containers. Plutonium and HEU will be converted into titanium-based ceramic pucks, with multiple pucks placed in a stainless steel can. These cans will then be encapsulated in glass and then packaged in a high-integrity waste container.

At this stage no decision has been made on the final packaging concept for HLW, SF, HEU and plutonium; however a Generic Specification for high heat generating wastes (HHGW) conceived to enable future packaging of these materials compatibility with a GDF has been developed [29]. A number of assumptions have been made regarding the conditioning and packaging processes for these wastes in order to provide a baseline and to assess their disposability:

- HLW - the packaging assumption, at this stage of GDF development, is that HLW will be vitrified and placed in high-integrity disposal containers for disposal
- in the event that SF is declared a waste it is assumed that fuel assemblies will be placed into high-integrity disposal containers for disposal

- in the event that plutonium and HEU are declared as wastes it is assumed that these are processed by conversion into ceramic pucks, with multiple pucks placed in a stainless steel can. These cans will then be encapsulated in glass in a large container and packaged in high-integrity containers for disposal.

The above packaging assumptions are consistent with the 2014 UK Government White Paper entitled Implementing Geological Disposal [30], although it is recognised that the actual packaging will need to be optimised in the future and may be rather different.

Materials suitable for construction of the high-integrity waste container are currently being investigated. For HLW and SF, initial work [31] has considered packaging in a waste container manufactured from copper for disposal in higher strength rock environments, similar to the concept currently planned for SF disposal in Sweden and Finland [32]. Subsequent work has updated the concept to include iron-based waste containers for disposal in other geological environments [33]. Dependent upon the geology in which the GDF is built, other possible container materials [34] and engineered barrier system options [35] are possible.

2.2.1 HHGW disposal containers

Two disposal container variants are proposed for the disposal of HLW, PWR SF, AGR SF, HEU and plutonium with either steel or copper outer casings. For both variants, a series of internal configurations have been proposed to accept the wastes that may be disposed of within this package.

It is anticipated that there will be four distinct types of waste for which the disposal container will be suitable:

- HLW - the form of the HLW is as produced by the Waste Vitrification Plant (WVP) at Sellafield and comprises a stainless steel vessel containing HLW conditioned by immobilising it in borosilicate glass (the process of vitrification). This item is referred to as a 'WVP canister'. Fission products separated from Magnox spent fuel will be treated in this manner. The disposal containers accommodate three HLW WVP canisters aligned along the axis of the disposal container. An example is shown in Figure 10.
- Pressurised Water Reactor Spent Fuel (PWR SF) – this will be packaged directly in the form of complete fuel assemblies. The disposal containers accommodate four PWR spent fuel assemblies. An example is shown in Figure 11.
- Advanced Gas-cooled Reactor (AGR) fuel – this will be dismantled, with the graphite sleeves, support grids and braces being processed separately as ILW, and the remaining fuel pins being consolidated into bundles within a stainless steel 'basket' which is then placed into high-integrity disposal containers. The disposal containers accommodate 16 slotted fuel cans. An example is shown in Figure 12.
- HEU and plutonium – titanium-based ceramic pucks in a stainless steel can encapsulated in glass within a large stainless steel vessel, similar to the reference HLW disposal container. This is shown in Figure 13. Figure 13 a-c show different sections of the packaging concept - a) shows a slice through the package showing an outer copper container (brown), iron insert (orange), and inner stainless steel container (pink) with an arrangement of seven cans (purple) surrounded by borosilicate glass (green), b) shows a cut-away of the package and the different layers of cans, whilst c) shows the ceramic pucks (purple) within the inner cans (orange). In b and c the borosilicate glass is not shown.

Figure 10: HLW vitrified waste container (shown with cutaway)

Figure 11: Schematic of PWR spent fuel assemblies

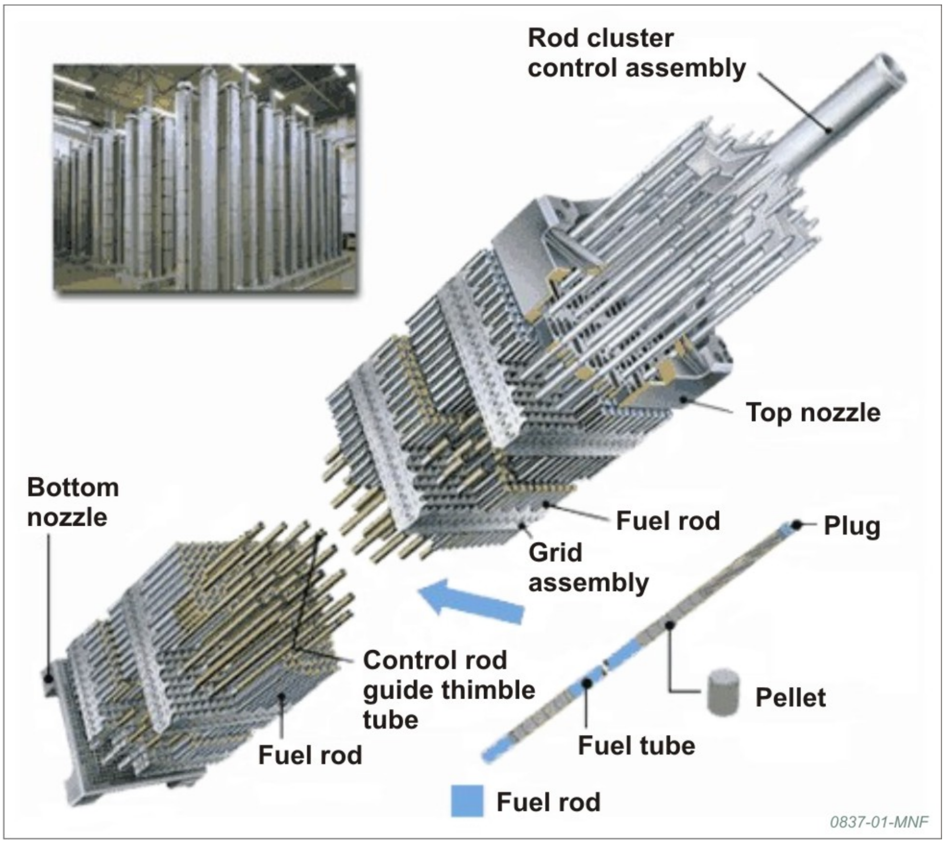


Figure 12: Schematic of consolidated AGR fuel bundles contained in a slotted can which then sit within a stainless steel basket

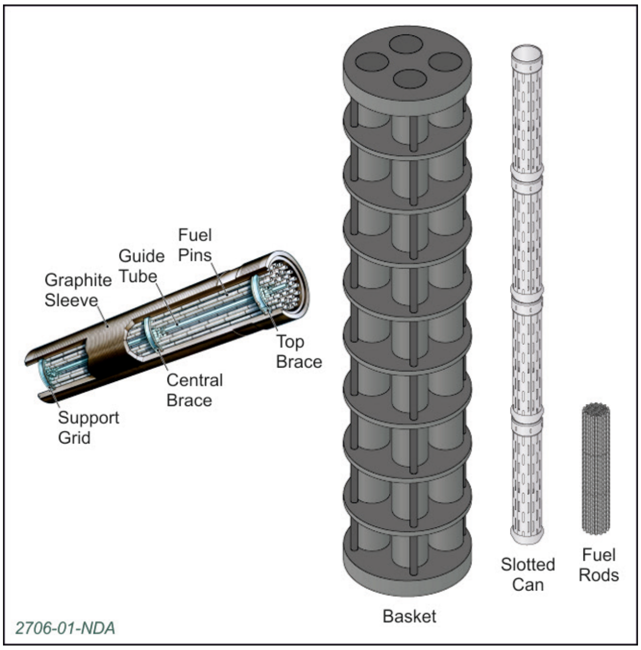
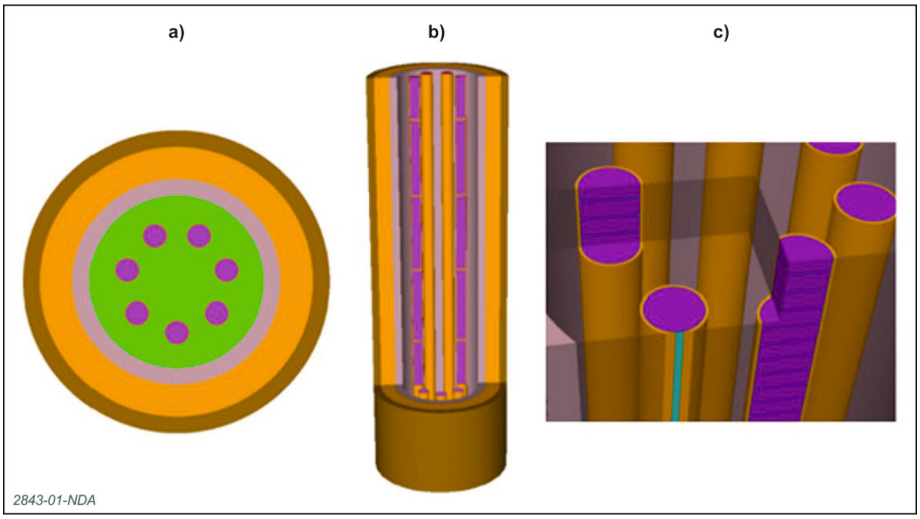


Figure 13: Conceptual illustration of the can-in-can packaging concept for Pu and HEU disposal



A number of different designs and materials have been considered for fabricating waste containers in different countries [36].

In Switzerland, for HLW and SF, it is proposed to use a thick carbon steel waste container. On emplacement the disposal containers would be surrounded by a bentonite clay backfill.

In Sweden and Finland, it is proposed that the waste container for SF consists of a copper outer shell with an inner cast iron insert. Different slots are available in the cast iron insert to load fuel elements and associated furniture. These disposal containers would be completely sealed by friction-stir welding of the outer copper lid.

Conceptual designs have been developed on the basis of these mature overseas designs, to inform the GDF design and safety case [37]. This has resulted in the current consideration of two variants of the disposal container to suit a GDF in different geological environments:

- variant 1 is compatible with the higher strength rock illustrative disposal system designs. The disposal container comprises a copper outer shell with an inner cast iron structure, inside which the waste is placed
- variant 2 is compatible with the lower strength sedimentary rock and evaporite rock illustrative disposal system designs. The disposal containers will be made from cast iron, with carbon steel 'tube and plate' basket inserts inside which the waste is placed.

As discussed above, it is envisaged that HLW which has been encapsulated in WVP containers, AGR SF which has been stripped of its spacers and packaged into slotted fuel cans, and complete PWR SF assemblies will be packaged into disposal containers for disposal.

The mass and dimensions of the disposal containers in the scheme vary significantly. The construction method and the lid closing method also vary between the disposal containers for the different waste contents. The dimensions and mass of the six disposal containers can be found in Table 3.

Table 3: Dimensions and mass of the HLW disposal containers

HLW disposal containers	**Dimensions**[3] [37]	**Typical mass (including waste)** [37]	**Wall construction**
Copper HLW disposal containers	Height: 4577 mm Diameter: 1050 mm	25,880 kg	50mm copper, cast iron insert for support.
Copper PWR disposal containers	Height: 4469 mm Diameter: 1050 mm	24,530 kg	50mm copper, cast iron insert for support.
Copper AGR disposal containers	Height: 4949 mm Diameter: 1050 mm	27,730 kg	50mm copper, cast iron insert for support.
Steel HLW disposal containers	Height: 4428 mm Diameter: 1050 mm	16,590 kg	Carbon steel body 150 – 250 mm thickness.
Steel PWR disposal containers	Height: 4620 mm Diameter: 1050 mm	18,890 kg	Carbon steel body 150 – 250 mm thickness.

[3] These dimensions are correct for the reference disposal container design used for planning purposes in developing designs for the GDF. These dimensions may change when optimising the design of these disposal containers.

HLW disposal containers	**Dimensions**[3] [37]	**Typical mass (including waste)** [37]	**Wall construction**
Steel AGR disposal containers	Height: 5070 mm Diameter: 1050 mm	20,400 kg	Carbon steel body 150 – 250 mm thickness.

Similar to other wastes, our assumption is that the HLW will be packaged by the waste packager remote from the GDF site. Therefore, a re-useable transport container will be required to take these disposal containers to the GDF for underground emplacement in deposition holes. To demonstrate the suitability of the packaging concepts for transport, the conceptual design for a disposal container transport container (DCTC) was developed (section 2.2.2). The combination of the DCTC carrying a disposal container will meet the requirements for a Type B(U) transport package under the IAEA Transport Regulations.

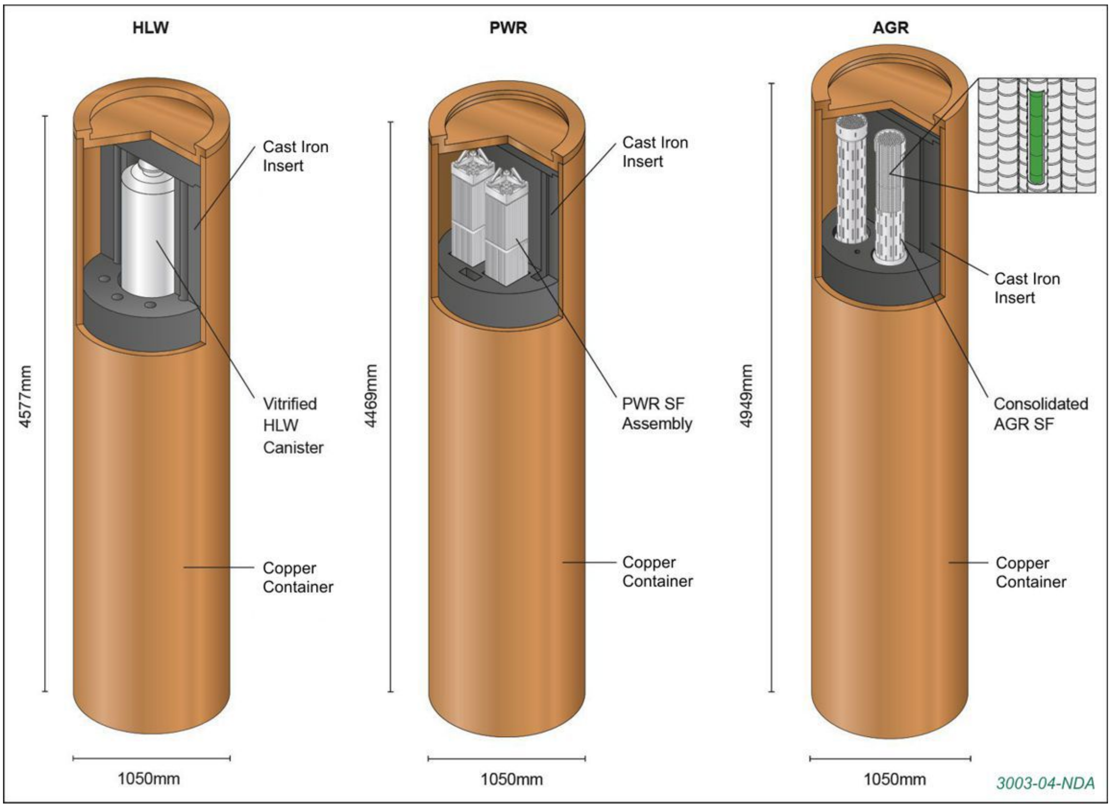
The following sections provide further details on the two variant disposal container designs.

Variant 1 disposal containers

Proposed Variant 1 disposal container designs employ copper for the outer corrosion barrier and nodular cast iron for the inner structural element. They are based on the Swedish SKB container design. Variant 1 containers would be used in a higher strength rock host geology.

The Variant 1 disposal container designs proposed employ copper for the outer corrosion barrier and nodular cast iron for the inner structural element of the container with carbon steel tube receptacles to accommodate the waste contents, as shown in Figure 14. The Variant 1 disposal container designs, to an extent, are based on the development and manufacturing experience gained in support of the Swedish SF programme reported by SKB [38] who developed the design, materials and manufacturing processes for SF disposal containers over a period extending more than 30 years and, more recently, the work of Posiva in Finland.

Figure 14: Illustration of Variant 1 disposal container



Structural integrity of the disposal container is provided by the steel inner lid and the inner cast iron insert, whereas containment is provided by the copper shell. Copper has been chosen for its corrosion resistance, to provide the required protection to the inner steel lid and cast iron insert over the intended timescale.

The copper outer body consists of a cylindrical body and a bottom plate. It is envisaged that the bottom plate and outer body will be produced in one piece by a pierce and draw method. The outer lid will be friction stir welded to the body at the packaging plant after loading of the waste contents [37].

Identical lifting features are provided at both ends of the disposal container so the disposal containers can be handled at both ends and horizontally.

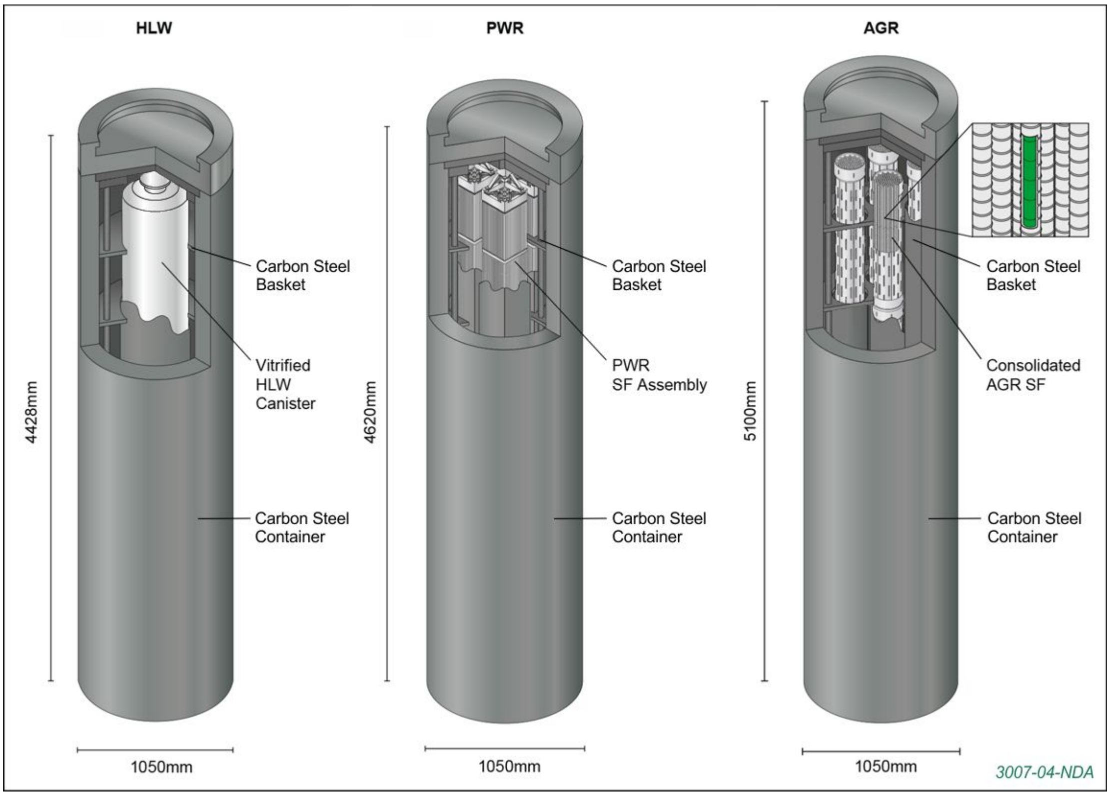
Variant 2 disposal containers

The proposed Variant 2 disposal container design employs steel for the outer corrosion barrier and nodular cast iron for the inner structural element. It is based on the Swiss NAGRA container design. Variant 2 containers would be used in a lower strength sedimentary rock or evaporite host geology.

The Variant 2 disposal container design proposes the use of a thick-walled container with a separate lid and base and a carbon steel basket (as shown in Figure 15 and Figure 16) with the intention of providing a corrosion barrier and load bearing structure, which is closed and sealed by welding prior to emplacement. Similar to the copper option, it is this requirement for closure welding that acts as the driver for many of the material requirements. The design calculations have taken into account the need to resist long-term loss of thickness through corrosion, the hydrostatic and lithostatic loads emanating from long term burial and also radiation shielding requirements.

This has resulted in a series of designs where the finished container wall thickness is 120 mm and the lid and base are 235 mm and 205 mm thick, respectively (including the lifting features around the perimeter of the ends).

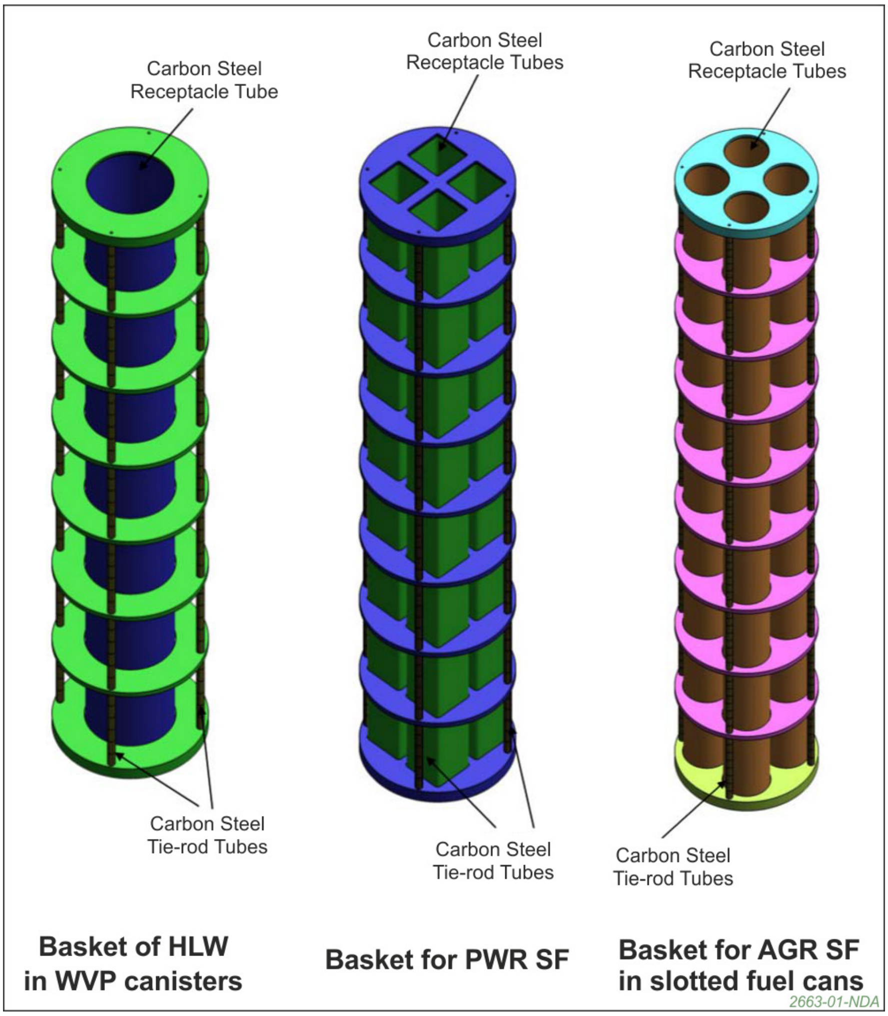
Figure 15: Illustration of Variant 2 disposal container



Containment in Variant 2 disposal containers is provided by the carbon steel body and the forged carbon steel lid, which it is suggested could be connected by welding after loading of the waste contents.

The waste contents are located in the basket in the disposal containers, which will maintain their position during all handling and loading scenarios. The baskets for the different waste contents all consist of receptacle tubes for accommodating the waste contents, and their positions are maintained by a top plate, a bottom plate and a set of evenly spaced support plates, which are in turn connected by a set of tie rods and tie rod pipes [37].

Figure 16: Illustration of baskets for the three differing contents of the Variant 2 disposal containers

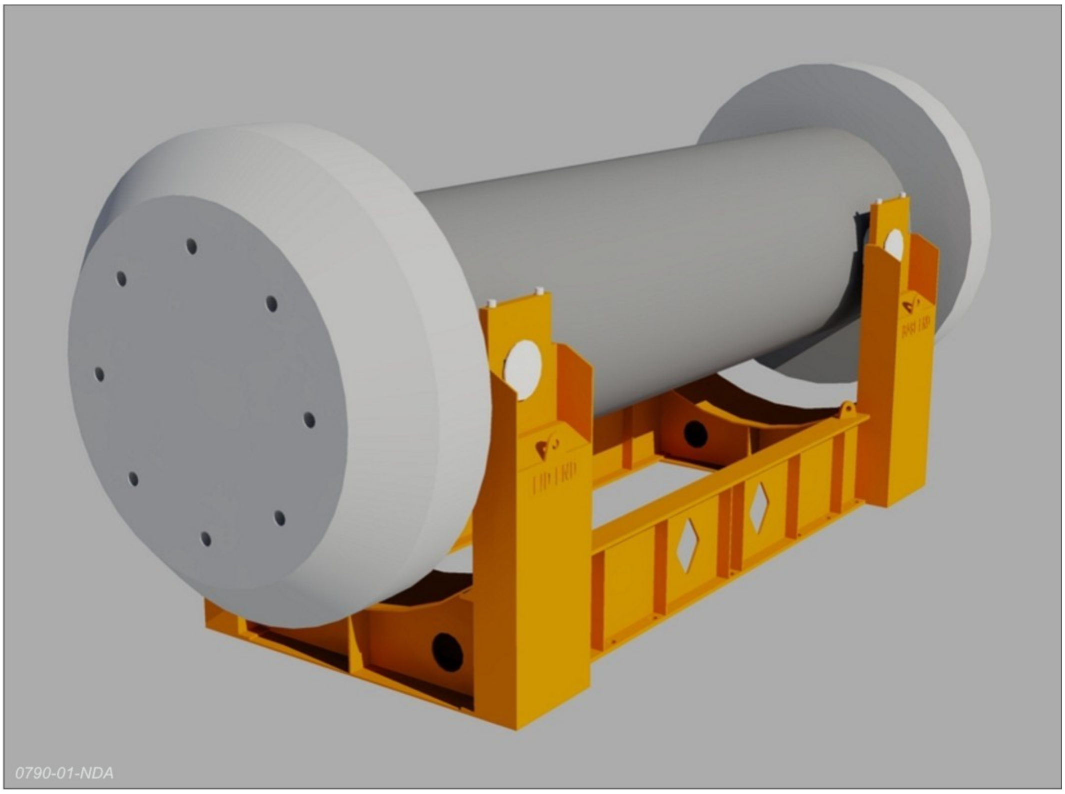


2.2.2 The Disposal Container Transport Container

The Disposal Container Transport Container (DCTC) is designed to transport the disposal containers to the GDF and to ensure that the package as a whole complies with the IAEA Transport Regulations. Designs for the DCTC are currently at a conceptual stage.

The generic transport system design [39] states that disposal containers will be transported from the packaging plant or store facility to the GDF in re-usable transport containers. Whilst the design of the disposal containers is well underway design of a container to transport them, the DCTC, is at a conceptual stage. Figure 17 shows an illustration of the conceptual DCTC.

Figure 17: Conceptual disposal container transport container on its handling frame



The combination of the DCTC carrying a disposal container will be required to meet the requirements for a Type B(U)F transport package[4] under the IAEA Transport Regulations [14]. The requirements in these regulations for Type B(U) transport packages cover both normal transport and accident conditions. They specify limits on package dose rates, the release of radioactive material under accident conditions and constraints to prevent criticality.

The current DCTC design has a diameter of 1.68 m with a length of 5.68 m. The internal cavity diameter of the DCTC is a minimum of 1.05 m.

The heaviest of the disposal containers is Variant 1 with AGR SF, which has a total mass of 27.7 tonnes, this is heavier than the 25 tonnes that the current DCTC is designed for. Therefore, the DCTC design will need to be modified for the increased mass of the disposal container. However, the estimated total mass of a modified DCTC, laden with the Variant 1 disposal container with AGR SF is 63.3 tonnes, which is just less than the 65 tonnes weight limit for rail transport wagons in the UK.

Design work for the DCTC [40] has also considered thermal performance. Waste was assumed to have a thermal output of 1200W (a load of 2000W was also evaluated to study sensitivity of the design to higher heat loads). The most vulnerable components of the package are the seals at the lid interfaces. The temperatures experienced (maximum 140°C) are all shown to be below the maximum temperature withstand of 150°C for one year for these components.

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[4] Type B(U)F: A Type B transport package with unilateral (U) approval for carrying fissile (F) material. Note that any package carrying fissile material requires multilateral approval (approval by the competent authority of every country it travels through).

An essential requirement for a developed DCTC is the incorporation of Multiple Water Barrier (MWB) features to allow the transport of irradiated fuel with 235U enrichments above approximately 2.5% [41]. This is because MWB features prevent the ingress of water (a neutron moderator) into the package, which ensures compliance with the criticality safety requirements in the IAEA Transport Regulations for higher fuel enrichments. Design work determined that the MWB requirement could be achieved by the use of two water barriers comprising an inner and an outer lid for the DCTC, which remain watertight under transport accident conditions, thus allowing an increase in the subcritical fissile mass and/or enrichment [42]. Following these design recommendations, further work (to be published) has been performed on the thermal and impact performance of the DCTCs in transport fault conditions.

3 Accident conditions

In this section we discuss the impact and fire accident scenarios in which we assess the safety of waste packages in impact accidents (Section 4) and in fire accidents (Section 5). This is complemented by a summary of some international experience (Section 3.7).

To ensure the safety of workers and the public, the Office for Nuclear Regulation's (ONR) Safety Assessment Principles [43] describe two approaches that we can use to develop understanding and safety measures in the generic disposal system:

- design basis assessment/analysis (DBA) – this shows that the design will withstand certain prescribed challenges, due to faults within the system or external hazards. DBA is based on conservative assumptions and is principally deterministic, in general taking no credit for the probability of such events. DBA provides a demonstration of the fault tolerance of the system.
- probabilistic safety assessment (PSA) – this considers both the probabilities and consequences of such events and is risk based. Conventionally, PSA is based on best-estimate rather than conservative assumptions, and makes use of parameter probability distribution functions.

The DSSC concentrates on demonstrating compliance with defined limits (DBA) for operational faults. This is consistent with the deterministic approach adopted in the IAEA Transport Regulations [14].

A transport system will need to be developed to safely move waste packages from the waste packager's' site(s) to the GDF. The transport safety case aims to demonstrate compliance with the IAEA Transport Regulations. Transport safety requirements are described in Section 3.2.

The GDF will receive and emplace tens of thousands of waste packages. It is recognised that, even with the incorporation of all feasible measures to reduce the possibility of accidents, due to the limits on reliability that can be assumed when undertaking safety assessments, accidents cannot be ruled out. In order to minimise the consequences of these accidents we have assessed a number of scenarios and have included design features to address these. GDF operational safety requirements are described in Section 3.4.

The consequences of accidents could include exposure to radiation of both workers and members of the public from a number of routes. The safety assessment methodologies for transport and operations include the use of toolkits to analyse and combine the location of a fault and the pathways by which workers and members of the public could be at risk. To assess the consequences it is important to be able to estimate the amount and form of material released at each accident location; one way of doing this is to determine what fraction of the radioactive material is released from a waste package following a defined accident. This concept of a release fraction (RF), which may comprise several components, provides a way of estimating the release from different waste package types and for different accident scenarios. These accident scenarios also link to the safety case for operations at the GDF. Although the potential for accidents underground has been identified, such as a dropped load, each type of accident needs to be quantified into representative accident sequences that can be analysed by full-scale testing of simulant waste packages or by other techniques, such as computer modelling. Currently, bounding accident scenarios have been defined and data for these are provided as inputs to the safety cases.

The detailed definition of the potential accident scenarios depends in part on the geology in which the GDF is built. Three different geologies are currently being used as a basis for design development purposes: higher strength rock, lower strength sedimentary rock and evaporite rock. These rock types require different GDF designs, with different potential accident scenarios. For example, the waste package stacking arrangements for the lower strength sedimentary rock and the evaporite rock are lower, hence the drop heights in the higher strength rock are bounding of drops in the other two host rock types [44].

The first step in analysing the GDF illustrative disposal concepts is to identify the credible accidents that could occur. There are long research lead times to develop methodologies, tests and modelling to determine how waste packages would perform in these scenarios. Therefore, accident scenarios and RFs have been developed for the higher strength rock as this presents the bounding case in terms of drop height and yield strength of rock. Accident scenarios will be developed for the lower strength sedimentary rock and the evaporite rock at a later stage, if required, on a site specific basis.

RFs have been determined using both physical tests (for example, drop tests of full-scale waste containers containing simulated wasteforms, impact tests on scaled physical models and fire tests) and numerical analysis (computer-based finite element (FE) models). These RFs enable the assessment of the major contributors to dose under the various accident scenarios. The physical tests have provided a basic understanding of how waste packages perform and the results of these tests have been used to develop, refine and validate the computer models. With a range of different waste container types, a variety of wasteforms and numerous impact scenarios (for example, different drop orientations, drop heights and fire durations), there are too many combinations to physically test the full range of waste package responses. Computer models are therefore needed to allow the assessment of all defined events for the different waste packages.

3.1 Assurance of waste package performance in accidents

The Disposability Assessment process exists to support waste packagers that wish to condition and package higher activity wastes in a form that is compatible with the GDF. In Disposability Assessments we determine whether packaged wastes are compliant with the safety case requirements for transport to, and operations and disposal in the GDF.

For many years we have produced specifications for packaged radioactive waste. These specifications define generic standards and performance requirements for waste packages which will be compatible with the systems and safety cases for transport to, and disposal in, the GDF.

The Level 1 generic specification [15] plays an important role in ensuring the safe and efficient preparation of waste for disposal in the GDF by providing a baseline that waste packagers can use to determine how to package wastes and thereby meet the requirements for passive safety and compatibility with future transport and disposal processes. Generic specifications are an important part of our Disposability Assessment process and act as the preliminary waste acceptance criteria (WAC) for the GDF.

The Level 2 generic specifications provide a definition of the standardised waste containers that can be used for the manufacture of waste packages containing a particular type of waste. Currently generic specifications exist for two broad categories of waste, a Generic Specification for waste packages containing low heat generating wastes [15], and a Generic Specification for packages containing high heat generating wastes [29].

The RWM Disposability Assessment process exists to support waste packagers that wish to condition and package higher activity wastes in a form that is compatible with plans for the implementation of the GDF. It is also used to support the ongoing development of the safety cases for geological disposal by the provision of information regarding the numbers and properties of the waste packages that will eventually require transport to, and disposal in, the GDF.

In undertaking Disposability Assessments we determine whether packaged wastes will have characteristics compliant with the safety case requirements for transport to and operations in the GDF, and ultimately whether the wastes could be accommodated within the GDF post-closure safety case, meaning that the packages are 'disposable'. The main output of the assessment is an assessment report detailing the work undertaken and which may be accompanied by a Letter of Compliance (LoC). The LoC is simply a statement to the effect that the waste package as described in the submission has been assessed and found to be compliant with transport and geological disposal requirements as currently defined. The joint regulatory guidance [45] requires that waste packagers (Site Licensees) produce a Radioactive Waste Management Case (RWMC) which includes a reasoned argument as to why packaged waste will be disposable – the RWM Disposability Assessment and accompanying LoC [46] provide an important component of such a case.

3.2 Impact and fire performance requirements during transport

The performance standards for waste transport are characterised in terms of three severity levels: routine conditions (incident free); normal conditions (minor mishaps) of transport; and accident conditions of transport.

The transport of waste packages through the public domain is subject to the IAEA Regulations for the Safe Transport of Radioactive Material [14] and implemented in the UK through the Carriage of Dangerous Goods Regulations [47]. The regulations are aimed at minimising the radiation exposure of workers and members of the public under both normal and accident conditions of transport.

The RWM transport safety case [48] demonstrates at this generic stage why we believe that the transport of radioactive wastes will be accomplished safely. The TSC addresses the specific contribution of the form of packaging in the Transport Package Safety Report [49], describing in detail the controls applied to packaging and the means by which these are defined and recorded within a Package Design Safety Report (PDSR). A PDSR defines the permitted radionuclide and physical/chemical inventory of a specific design of transport package such that it can be transported in accordance with the deterministic criteria defined in, or derived from, the IAEA Transport Regulations.

The most significant element of the overall approach dictated by the IAEA Transport Regulations is to apply a graded approach to package design depending upon the hazard posed by the radioactive contents. The graded approach applies to content limits for packages and to performance standards applied to package designs. The performance standards for waste transport are characterised in terms of three severity levels, which can be summarised as:

- routine conditions of transport (incident free) and normal conditions of transport (minor mishaps such as small bumps and scrapes)
- accident conditions of transport.

The majority of the SILW/LLW/RSC waste packages are Industrial Package (Type-IP) transport packages in their own right (see Section 2.1.2). The IAEA Transport Regulations for these transport packages do not include specific requirements on the accident performance because the potential consequences following an accident are minimised by stringent requirements on the allowable content and form of radioactive material in a waste package.

For disposal containers and UILW waste packages, two Type B transport containers are assumed for modelling purposes. A conceptual DCTC, as described in Section 2.2.2 has been developed to demonstrate the suitability of the disposal containers for transport. We have developed detailed designs for the SWTC for the transport of UILW packages as described in Section 2.1.1.

The performance standards required in the IAEA Transport Regulations [14] define the accident conditions that the transport packages can withstand to a specified level of tolerance, where the level depends on the hazard presented by the transport package contents.

After this series of tests, the IAEA criterion to be met is that the 'specimen' (transport container) shall restrict the accumulated loss of radioactive contents to a specified quantity, limit the loss of shielding and prevent criticality[5].

We are developing an understanding of the performance of the two types of transport packages (based on the conceptual DCTC and SWTC designs) to ensure compliance with the IAEA Transport Regulations. As these regulations are updated regularly we will ensure compliance with the regulations at the time when the waste packages need to be moved.

3.3 Release fraction definition

Release Fractions (RFs) are defined for particular fire and impact faults. RFs are defined slightly differently for the two fault types.

RFs are principally concerned with the quantity of radioactivity that may be released from a package in an accident.

Release Fractions (RFs) are defined for both fire and impact faults. A release fraction in its simplest form is the amount of activity that crosses a container boundary divided by the amount of activity originally within the container.

The definition is further refined for the two fault types. Impact faults are associated with a respirable particle size. For fire faults, all materials turned to a gaseous form are considered to be respirable and the overall package RF includes a weighting for volatility. We begin introducing these definitions below.

3.3.1 Impact

Impact RFs arise from wasteform particulate crossing the container boundary through an opening, and are expressed as a proportion of the mass of the wasteform with a particle diameter below a specified value. The particle size used in transport safety assessments is 100 µm. For operational safety assessments the size used is 10 µm (this was reduced from 100 µm in 2016).

The RF for a waste package resulting from an impact accident is defined as the mass of particulates smaller than a given diameter which cross the package boundary, expressed as a fraction of the pre-accident mass of the wasteform (independent of particle size). Activity is assumed to be uniformly distributed amongst the wasteform.

The particle size used in transport safety assessments is defined in the IAEA Transport Regulations to be 100 µm. In GDF operational safety assessments 10 µm is used (this was reduced from 100 µm in 2016 to bring RWM into line with wider industry practice).

For a particular waste package, the RF from impacts in different orientations will vary. This is because the extent of knockback deformations, the energy absorbed by the wasteform and the effectiveness of the waste container in containing the particulates will all be different. Typically, for 500 litre drum packages, the RF for drops onto flat unyielding targets will be largest for drops where the package centre of gravity is over the lid edge.

[5] For further information on the transport requirements relating to criticality, see the Criticality status report [7].

The next worst orientation is the side drop, while the RF is generally close to zero for top down drops and zero for base down and base edge drops.

Work is underway to evaluate the RFs for standard packages should they be dropped onto an aggressive feature (defined as the worst orientation onto the most rigid package within the same vault, for example, the corner of a corner lifting $3m^3$ box for the ILW vaults) (see [10] tasks 914, 915, 929 where new FEA models are being developed with this task in mind), although it may be possible to remove the fault via modifications to the GDF design and package emplacement process.

3.3.2 Fire

Fire RFs arise when radioactive material that has changed to a gaseous form, or has become entrained in steam or other gases, crosses the container boundary. No particle size limit is considered. Radionuclides in specific chemical species have differing volatilities; therefore ‘group RFs’ are defined for six ‘volatility groups’ of radionuclides, each covering a differing range of volatility. Group release fractions represent the fraction of activity of radionuclides within that group that are expected to cross the container boundary upon heating to a defined temperature. The overall package RF resulting from a fire accident is the weighted sum of released radionuclides, expressed as a proportion of the sum of all radionuclides present within the wasteform, taking account of volatility.

The package RF for a waste package resulting from a fire accident is defined as the summation of the amount of radioactive material, per volatility group, that could cross the waste container boundary in the event that a waste package is involved in a fire, expressed as a proportion of the total activity present in the wasteform.

The fraction of activity for each radionuclide that is assumed to be released is based on association of each element to a ‘volatility group’. There are six of these, with each group having a ‘group release fraction’, which is usually temperature dependent. Group release fractions represent the fraction of activity that will be expected to cross the container boundary upon heating to a defined temperature. Group release fractions are discussed further in section 5.3.3.

Any release results from a combination of two components: the heat energy absorbed by the wasteform in the fire and the changes to the wasteform which give rise to mobile activity. All released material in the event of a fire is assumed to be respirable due to the gaseous nature of volatile releases and the small particulate entrained in steam driven releases.

In assessing the fire performance of waste packages it is pessimistically assumed that a package is engulfed in flames, with none of the external surfaces being shielded, for example, by adjacent packages or stillages.

When exposed to a fire, the external surface of the waste package will heat up. This heat will then be transferred inward to the rest of the package. The heat transfer is usually dominated by thermal conduction, although other heat transfer processes (such as thermal radiation) may also occur. Heat transfer through the waste package is usually a slow process and the centre of the package may not experience its maximum temperature rise until several hours after the fire has been extinguished. This implies that a release of volatiles may continue for some time after the fire is extinguished.

Waste packages are designed to minimise the heating of the wasteform, for example by having a low thermal conductivity.

The principal concern about waste package performance in the event of a fire is that the heating of the wasteform will cause radionuclides to be released. There are various processes by which this might occur:

- some solids may react with air inside the package to form a gas which may then escape from the package
- some solids may be volatile and may form a gas when heated, which could then escape from the package
- the wasteform may contain water (for example, bound into cementitious grout) which, when heated, produces steam. The steam may escape from the package, possibly carrying with it some of the radionuclides.

All radioactive material release due to a fire fault is assumed to be gaseous or extremely fine particulate entrained in steam or gases exiting the package. Therefore no particle size limit is used.

3.4 Impact and fire performance requirements within the GDF

Possible impact faults onto flat unyielding targets (such as the vault floor) and aggressive targets (primarily the corner of the most rigid package that the assessed package is likely to come into contact with) have been defined for UILW, SILW and disposal containers. Possible fire conditions have been defined for all packages during operations.

Following receipt at the GDF, waste packages will be subject to a range of handling and stacking operations. Some of these have the potential to result in accidents that could lead to waste packages being exposed to impacts and/or fires. Radioactive material released as a result of such accidents has the potential to cause radiation dose to GDF workers and, were it to occur in such a manner as to cause an off-site release, members of the public.

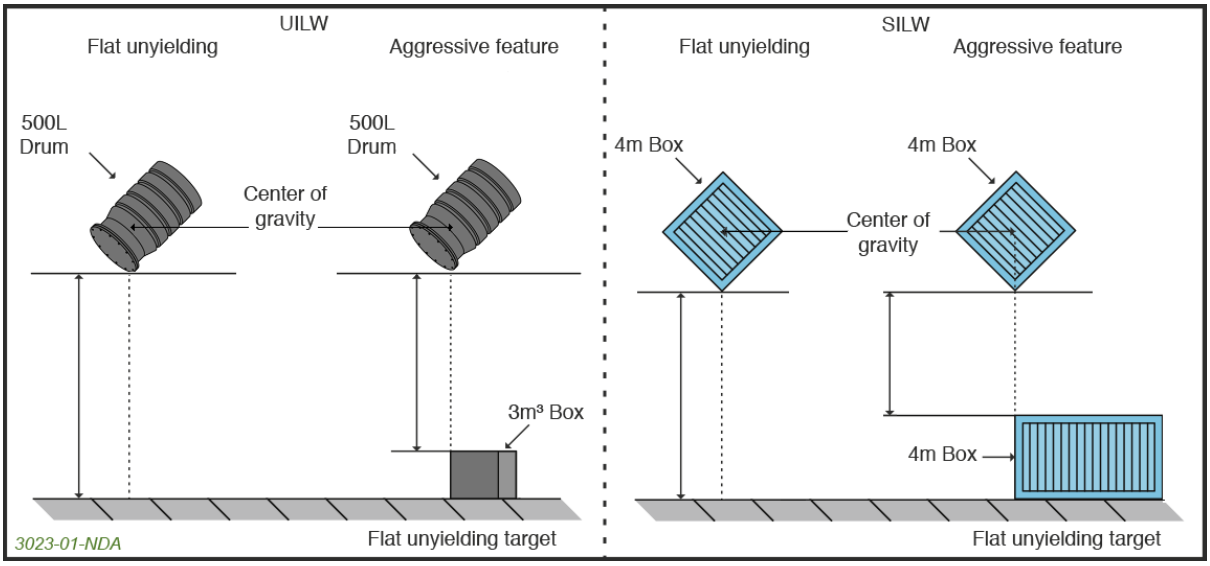
The radiological consequences of such potential accidents are subject to limits defined in legislation [50] and codified by the Office for Nuclear Regulation (ONR) within the Safety Assessment Principles for nuclear licensed sites [43]. The Safety Assessment Principles set down Basic Safety Objectives and Basic Safety Levels for on- and off-site exposure to radiation under both normal operations and potential accidents where radioactive material is released from its ‘normal’ containment (that is, in the case of the GDF, released from a waste package). These are reflected in the targets and limits defined in RWM’s Radiological Protection Criteria [51]. The design of the GDF, with respect to safety, is intended to strike a balance between the safety provided by the waste package and that provided by external engineered and passive features to minimise the release of radioactivity. The operational safety case reviews the most extreme (bounding) faults to identify the pathways and the effect of features such as a filtered ventilation system, in order to estimate the potential releases to workers and the public.

In the current DSSC, the designs for the GDF in the three host rock scenarios are included in a hazard identification exercise. The bounding case accidents identified for ILW and UILW are those for which package performance must be demonstrated. These are detailed in the RWM Waste Package Specification Documents [52, 53].

For disposal containers for HLW / SF, once they are underground within the GDF and outside of the DCTC, the credible impact accidents are a drop when emplacing the disposal container into the deposition hole and when lifting a container horizontally, depending upon the emplacement method. These are detailed within [54].

Flat unyielding targets are not the only target type that may be encountered within the GDF. Unless designed out of the GDF as design work progresses, a dropped package may land on GDF features, installed equipment or other packages themselves. These targets are called aggressive features. A review for both the UILW and SILW vaults was carried out [55, 56] to determine what would constitute the most onerous aggressive feature a package could drop onto. For packages in the UILW vault this was shown to be a drop onto the corner of an emplaced corner lifting 3 cubic metre box, or the edge of an emplaced side lifting 3 cubic metre box. For box containers, the dropped package will have its centre of gravity over a top corner and for a drum container its centre of gravity is over the lid edge. For the SILW vault the scenario was defined as a drop with the package's centre of gravity over its lid long edge and over the point of impact onto the lid edge of an emplaced 4 metre box. In both UILW and SILW scenarios the dropped package has its centre of gravity located over the edge of the target package. Examples of these faults are shown schematically in Figure 18.

Figure 18: Schematic of bounding impact scenarios for UILW and SILW vaults



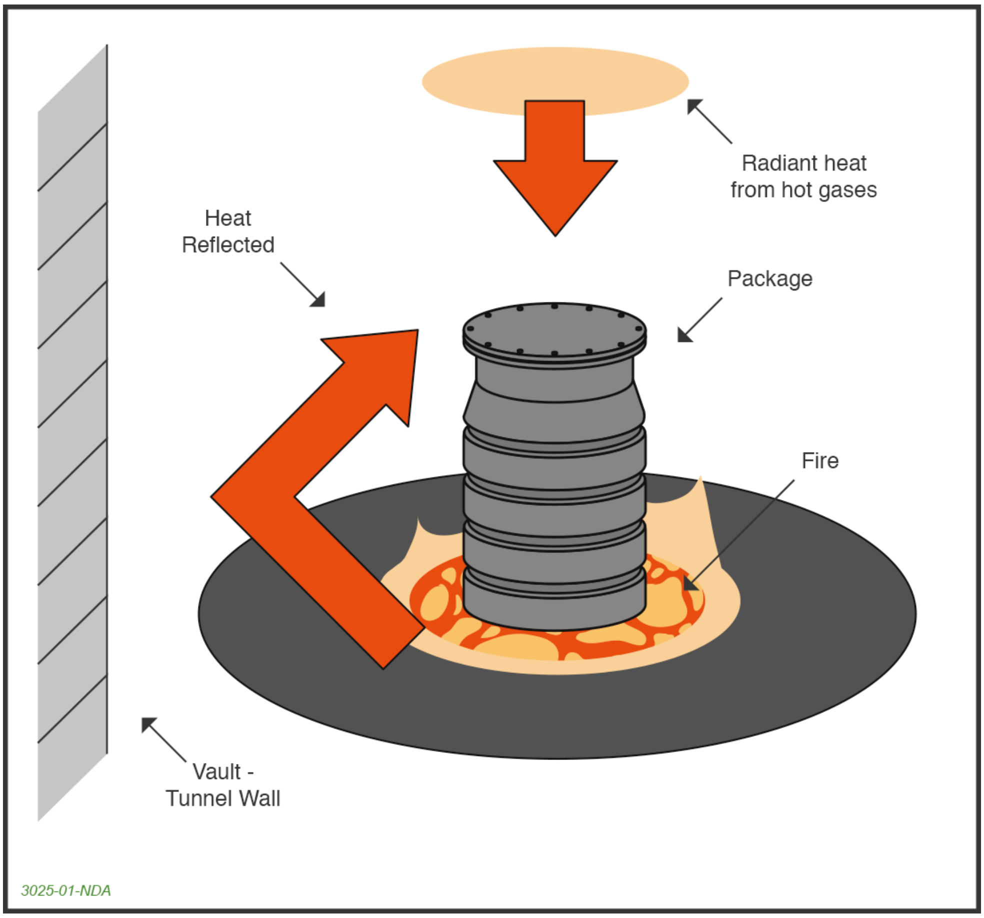
The conditions used in formulating RFs for waste packages in underground fires in the GDF are based upon the IAEA Transport Regulations. These conditions were refined following work to determine the limits on flammable material available within the GDF [14].

Based on the results from complementary Posiva work, a thermal scenario was identified for UK disposal containers once they are underground and outside of the DCTC [62].

Figure 19 shows schematically the scenario used for the fully engulfing fire around a package in the GDF. The figure highlights the main processes contributing to the specification of a higher temperature in the GDF fire scenario compared to the transport scenario. Heat is not only conducted and radiated directly from the fire but reflected from tunnel or vault boundaries and conducted / radiated from hot gases that accumulate in the upper section of the tunnel / vault back to the package. The figure illustrates the conservative assumption used in fire RF calculations that fuel is evenly distributed on a plane around the base of a package. The GDF fire scenario is thought to be highly conservative and is to be revisited in future work.

For thermal modelling, an initial temperature for the package under consideration is required. The host rock and waste package are assumed to be in thermal equilibrium prior to any fire (unless significant radiogenic heating increases the package temperature). This initial temperature of the host rock is defined using a geothermal gradient. This begins with an assumed 10°C at the ground surface and increases by 2.8°C for every 100 m of depth [57]. Thus, at 650 m deep the rock temperature is 28.4°C and at 1000 m it is 38.2°C (this is rounded to 38°C for use in assessments). The higher temperature of 38°C is assumed as a conservative bounding value.

Figure 19: Schematic of pool fire scenario



3.5 Coincident faults

Of the GDF impact or fire accidents identified, about 10 % are coincident faults, whereby the mechanical damage fault also initiates a fire.

We have undertaken a number of hazard and operability studies for the GDF. Of the impact or fire accidents identified, about 10% are coincident faults, whereby the mechanical damage fault also initiates a fire. The predicted consequences of these individual accidents are currently considered separately in the operational safety case for the GDF. The current approach is to treat the two events separately and combine the two predicted releases to provide an overall release for the accident. Damage to the container is not considered in a fault of impact followed by fire, as unless the container is sealed, all volatilised radionuclides are assumed to be released. Work is underway to review and revise these coincident faults to eliminate or minimise the risk and also to evaluate whether simple summation of the consequences is an appropriate methodology (See [10] Task 1026).

3.6 Free liquids within waste packages

Free liquids in significant quantities may alter the performance of a waste package under accident conditions. Liquids are particularly mobile, may enhance some release mechanisms and possibly introduce new fault sequences. All reasonable measures are taken to reduce the presence of free liquids in the waste.

RWM requires that all reasonable measures should be taken to ensure that, in the event of a fire or impact accident, the quantity of potentially mobile radionuclides present within the waste package, including those generated as a result of a fire or impact accident, is commensurate with the waste package meeting fire and impact performance requirements. However, requirements for accelerated risk reduction at key high-hazard legacy facilities are driving an evaluation of the acceptability of low levels of free liquids within a limited number of specific waste streams via the Disposability Assessment process.

The high level requirements for waste packages are outlined in the Generic Waste Package Specification [15,24] and include the following:

- under all credible scenarios the release of radionuclides and other hazardous materials from the waste package shall be low and predictable
- the package should exhibit progressive release behaviours within the range of all credible scenarios (that is, an absence of 'cliff-edge' effects)

The DSS [12] does not explicitly prohibit free liquids, although the underpinning Government policy for geological disposal of higher activity waste discusses solid waste within the Implementing Geological Disposal white paper [30]. Guidance from the regulators recommends immobilisation of liquids with selection of the exact waste treatment on the basis of the properties of the waste to be treated and the hazard that it presents [45]. This is incorporated in RWM guidance via the wasteform specification for LHGW [15] which notes that control would typically be placed on free liquids, with the extent of the controls dependent upon the robustness of the waste container and the consequences of the presence of these materials. The specification clarifies this with the following:

> *"Free Liquids: All reasonable measures shall be taken to exclude free liquids, and materials that may degrade to generate liquids, from the wasteform. Free liquids not removed from wastes prior to waste packaging should be immobilised by a suitable waste conditioning process."*

Initiating faults identified do not change as a result of increases in free liquids. However, the fault progression may need further consideration should free liquids be present:

- impact resulting in release of free liquid.
- Initial atmospheric dispersion and subsequent resuspension rates are likely to be low [58]; recovery operations and potential mobility of contaminated liquids are likely to be key considerations.
- fire resulting in increased steam-driven release.
- The greater presence of liquid within the package may possibly enhance any steam release from a package subjected to a fire. This enhanced steam release may entrain radioactive material or enhance release through steam distillation. There is a suggestion from experiment that high steam flow rates may entrain particulate from the wasteform [59].
- coincident fault of impact followed by fire.
- A higher consequence is posed by the possibility of a liquid spill resulting from an impact fault followed by a fully engulfing fire fault which may cause a significant airborne release. The possibility of such a coincident fault occurring is under review within the operational safety case. The consequences of such a fault will warrant further investigation if this fault type is considered possible. For contaminated liquids boiling to dryness a release fraction of 0.1 is suggested in the literature [58,60].

It should be noted that no operational faults consisting of fire followed by impact have been identified within the GDF designs.

Any residual free liquid within packages should also be considered for its effect on fire and impact performance from an internal corrosion standpoint during interim storage; the expected levels of corrosion are discussed within the Package Evolution status report [2].

3.7 International experience of waste package accident conditions

A review has been carried out to determine if a waste package satisfying the RWM requirements for impact or fire safety would satisfy the Waste Acceptance Criteria (WAC) for five other countries' facilities. The current range of SILW/LLW waste packages would be acceptable in all the reviewed overseas facilities.

Finland and Sweden are more advanced than the UK in their geological disposal programme for spent fuel. Spent fuel from the Finnish nuclear power reactors is planned to be emplaced in a GDF to be constructed at a depth between 400 and 600 m in the crystalline bedrock at the Olkiluoto site. SKB of Sweden and Posiva of Finland are developing spent-fuel container designs in a joint programme [61]. In many respects the design of the disposal containers can be considered similar to the RWM variant 1 illustrative design, as we have included the same containment approach and materials. The Posiva disposal container design report [62] describes the normal operating and accident conditions for the disposal container.

The Posiva report on impact accidents [63] identifies three handling impact accidents: a vertical drop onto an unyielding target from a height of 1.5 m, a topple onto a flat unyielding target and a topple onto a beam. In all cases the impact performances (assessed by finite element analysis) were good, with little general damage and only very localised damage to the copper container in the scenario involving a topple onto a beam. The vertical drop scenario assumes the disposal container drops 6 m into the deposition hole during underground emplacement.

The Posiva fire report [64] described modelling of their transport cask in a transport fire. The cask and the radiation shield can withstand fire for significantly longer than the 30 minutes required by the IAEA Transport Regulations. The DCTC has similar features to the transport cask and has been shown to provide equivalent safety to UK waste in disposal containers under fire accidents.

Underground, the Posiva fire report identified all the combustible substances for the container handling and deployment vehicle, including diesel, tyres and the neutron shield. All the materials were assumed to burn at a constant rate for 1 hour.

UK ILW/LLW is more varied than the ILW/LLW in many other countries due to the extensive research and reprocessing activities undertaken in the UK. In 2002 the GWPS was reviewed against the waste package specifications for geological disposal concepts in five other countries [65]; this included impact and fire accident performance. The comparison was carried out to determine if a waste package satisfying the RWM requirements for impact or fire would satisfy the WAC for each of the other countries' facilities.

The WAC for impact and fire for these other countries were considered jointly in the review. Their safety requirements set upper limits for the release of radioactive material following an impact or fire event. The three international facilities where fire and impact faults were considered necessitate waste packages to satisfy the requirements for IAEA Type A transport packages. The range of SILW/LLW waste packages included in the review (500 litre drum, 3 cubic metre box, 3 cubic metre drum, 6 cubic metre box, 4 metre box, 2 metre box, MBGWS box) would be acceptable in all the reviewed overseas facilities.

4 Waste package impact performance

This section of the report discusses our current understanding of how waste packages perform under impact conditions. We summarise the experimental testing and computer modelling that has been carried out. We begin with a discussion of potential package performance in Section 4.1.

Many waste packages that are today in interim stores have a current LoC. These required evaluation of the accident performance using the following approaches, as outlined in Section 4.2:

- full-scale drop testing
- finite element (FE) modelling combined with small-scale break-up test data
- analogy to another waste package's performance.

4.1 Potential waste package behaviour

On impact, a waste package will deform to absorb the kinetic energy it possesses. The deformation and any damage experienced by the package will depend upon the drop orientation, the type of target impacted and the design of the waste package. Modelling and drop testing have shown that the lid-body interface is often the weakest part of a waste package.

When a waste package is involved in an impact event such as those discussed in Section 3.4, it will deform to absorb the kinetic energy which it possesses at the start of the impact (assuming it is the dropped package rather than the target package). The design of the waste package, its drop orientation and the nature of the target, be it the flat stationary target or aggressive target in the GDF accident scenario, or the moving cavity of the transport container that the waste package will engage with in the transport accident scenario, will determine how the package will deform to absorb the kinetic energy. In the scenarios in which the target is deformable, these factors will determine how much of the energy will be absorbed by the package and how much of the energy will be absorbed by the target.

Some examples of waste package deformation behaviour in accident scenarios from computer simulations are shown in the following figures. Figure 20 shows the progress of the predicted knockback deformation of a typical 500 litre drum in a centre of gravity over lid edge impact following a drop from 11 m onto a flat unyielding target. The model has been re-orientated upright to better see the progressive damage. Figure 21 shows the predicted knockback deformation of a typical 500 litre drum in a side drop impact from 11 m onto a flat unyielding target.

Figure 20: Predicted knockback deformation progression of a typical 500 litre drum in a centre of gravity over lid edge impact following a drop from 11 m onto a flat unyielding target

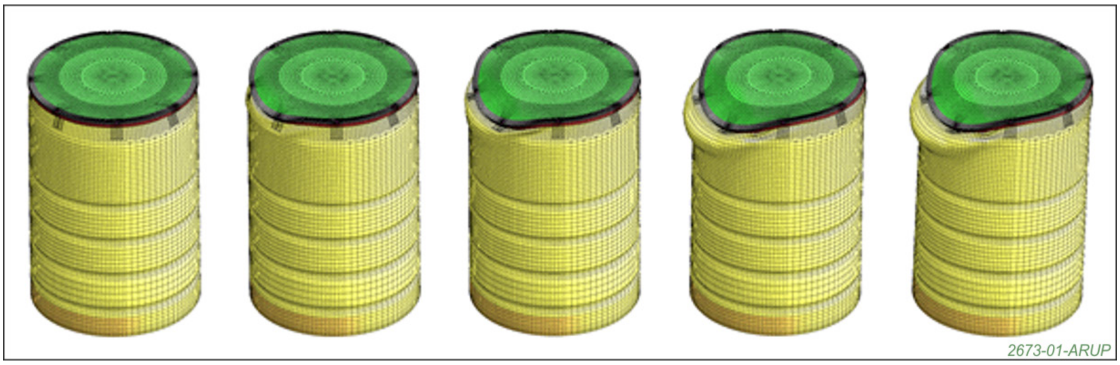
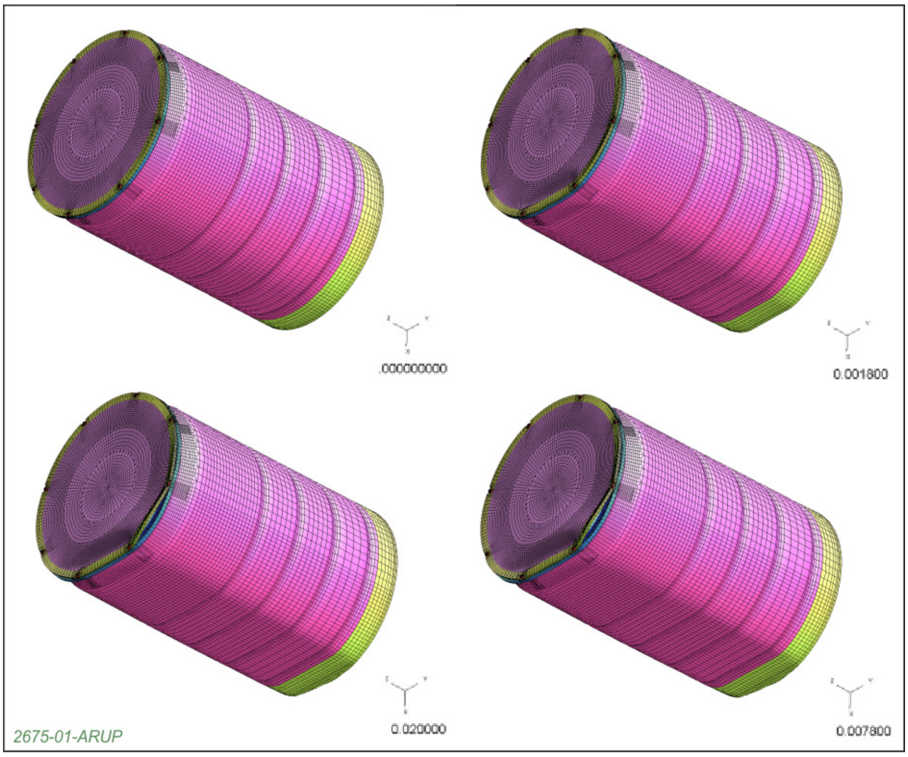


Figure 21: Predicted knockback progression covering the first 20 ms (clockwise, beginning top left) deformation of a typical 500 litre drum in a side drop impact from 11 m onto a flat unyielding target



Typically, the most onerous orientation for a 500 litre drum in impacts onto a flat target is the centre of gravity over lid edge orientation. The integrity of the container is most challenged in this orientation due to the way the drum deforms in order to flatten against the target and the location of the lid-body interface (which is often the weakest point of the drum) being located within the deformation area. Furthermore, due to the small area of contact between the drum and the target, the quantity of particulate that is generated is often substantial. The particulates are also located where the integrity of the container is most challenged. In a side drop, thanks to the larger contact area with the target, the knockback is often smaller than the lid edge drop and the integrity of the lid-body interface is often less challenged. Particulates are generated along the length of the package and, unlike the lid edge drop, not concentrated adjacent to the most vulnerable lid edge area of the package.

However, when a typical 500 litre drum, as part of a set of four drums, is subjected to a transport accident impact event in a centre of gravity over lid edge orientation when it is carried within an SWTC, the drum nearest the target would be supported on its side and on its lid by the cavity of the SWTC (ignoring the effect of a stillage). The contact area between the cavity of the SWTC and the drum is considerably larger than in the drop onto a flat target. Additionally, due to the orientation of the target in relation to the drum and the size of the contact area, the type of deformation the drum undergoes is considerably less onerous than in a drop onto a flat target and the extent of the deformation is also considerably smaller. The worst orientation for a 500 litre drum impact when carried in an SWTC is in fact a side drop. In this orientation the target is not significantly different from that when the drum is dropped on its own onto a flat target, but the two drums that are closest to the target in a set of four are impacted firstly by their own inertia onto the cavity of the SWTC, then by the drums above them, and then by the SWTC as it rebounds. This is illustrated in Figure 22, which shows the predicted deformation of a set of four typical 500 litre drums in a side drop, when modelled in an SWTC from a drop height of 9 m.

Figure 23, Figure 24 and Figure 25 show the predicted deformation of a typical disposal container, a side lifting 3 cubic metre box and a 2 metre box after typical impacts.

Figure 22: Predicted deformation of a set of four typical 500 litre drums in a side drop, when modelled in an SWTC from a drop height of 9 m

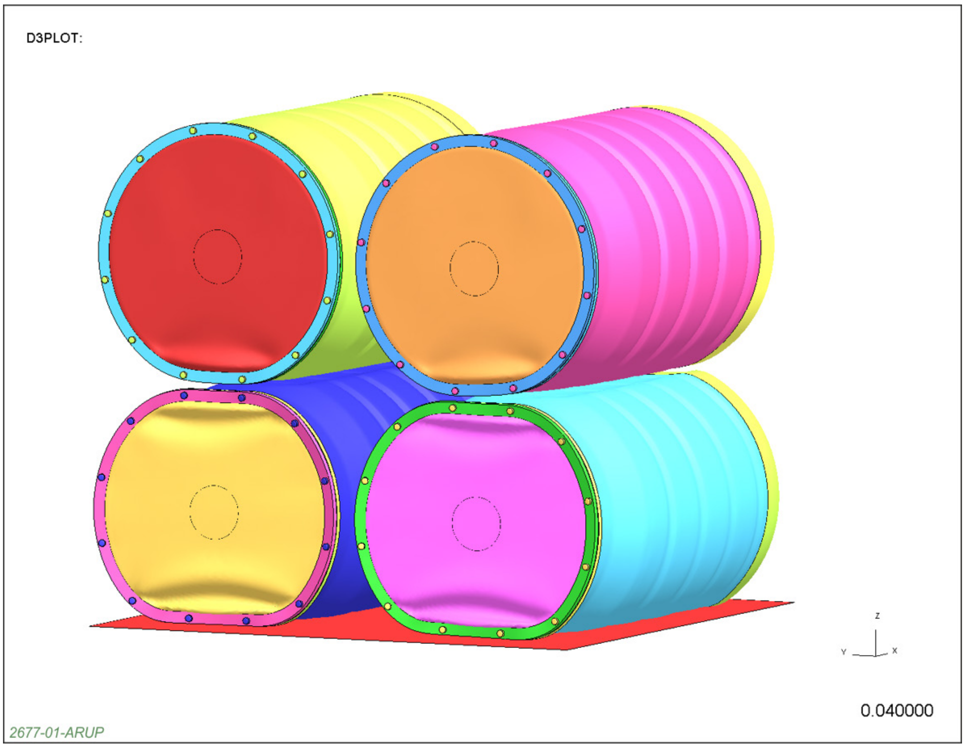


Figure 23: A cross-section of a disposal container with AGR spent fuel in slotted cans, a colour gradient shows the typical deformation and plastic strain within the disposal container following an 8 m drop

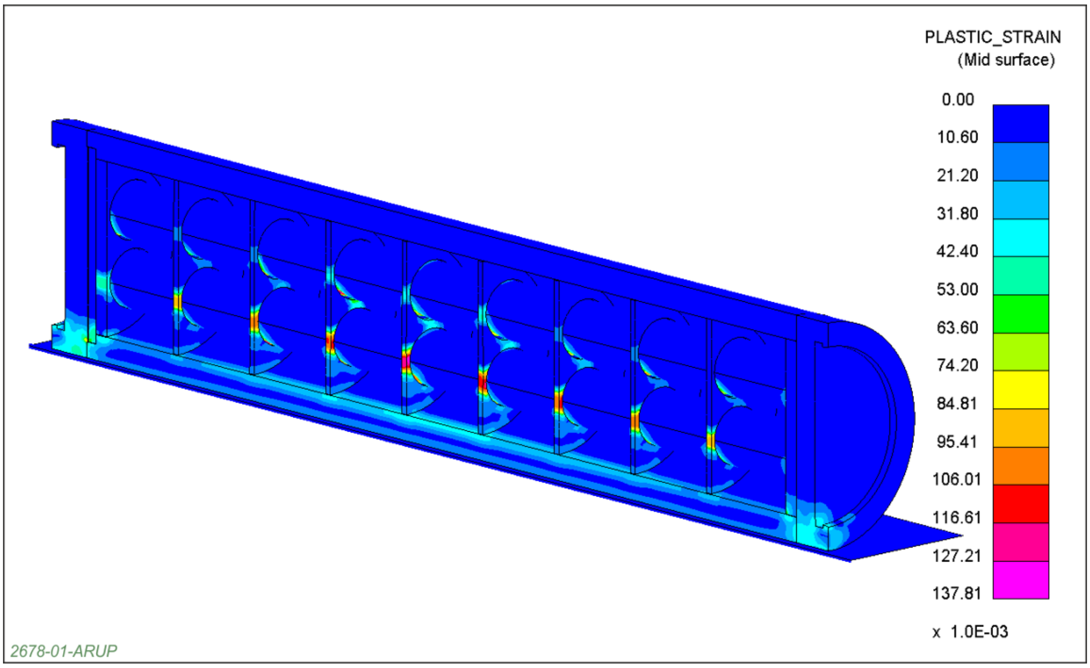


Figure 24: A cross-section of a corner of a 3 cubic metre box, showing typical deformation after a 25 m drop onto a flat unyielding target

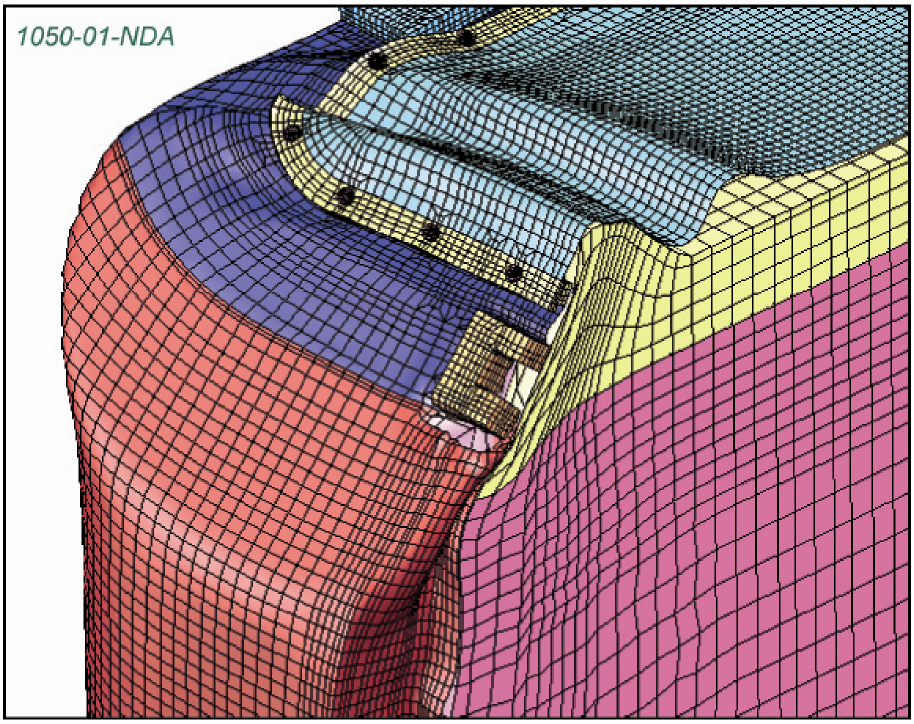
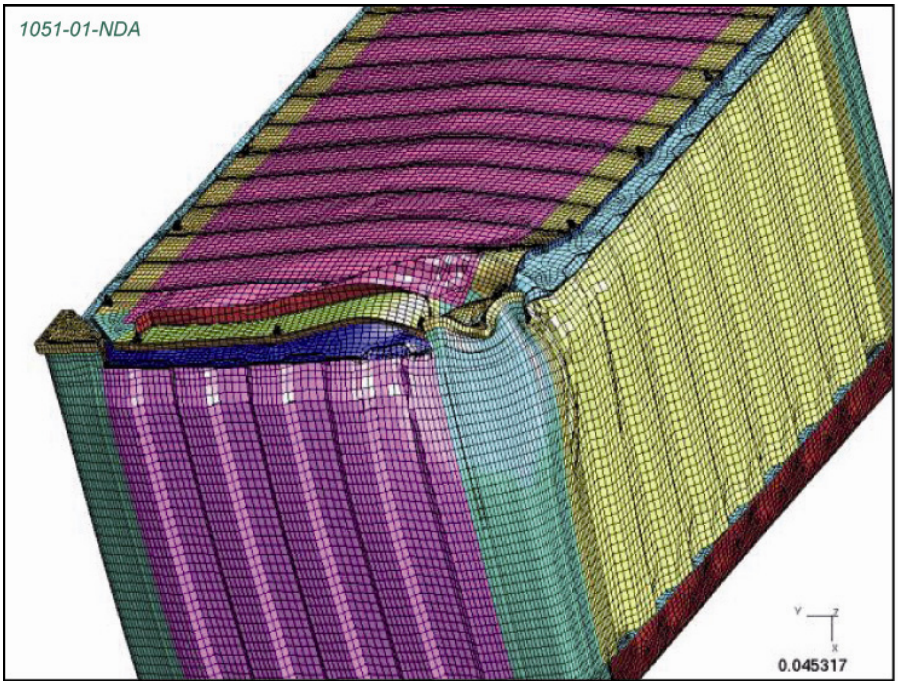
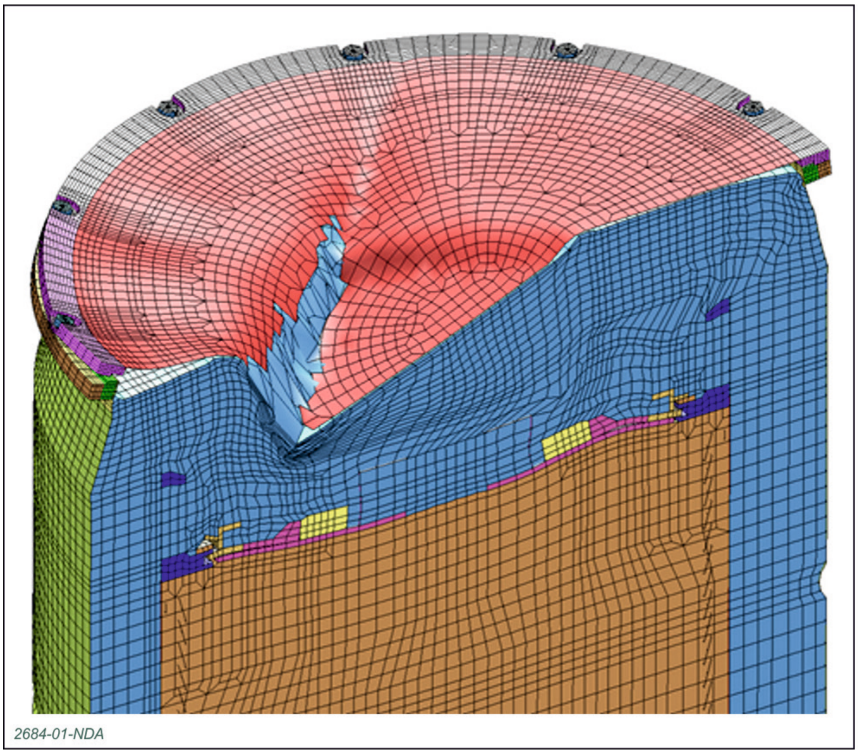


Figure 25: Typical deformation of a 4 metre box after a 15 m drop onto a flat unyielding target



As has been noted in Section 3.4, the most pessimistic target for most packages (except for disposal containers) in GDF accident scenarios is an aggressive target. In impacts onto an aggressive target both the drop orientation and the point of initial contact would affect the behaviour of the package during the impact. For 500 litre drums the lid is typically the most vulnerable area in an aggressive target impact. In order to minimise package rotation during the impact, and so that the lid is exposed to the aggressive target, the drum needs to be in an approximately centre of gravity over lid edge orientation. Figure 26 shows the predicted deformation of a typical 500 litre drum in such an impact.

Figure 26: Predicted deformation of a 500 litre drum in an aggressive feature impact, which predicts a breach in the container lid



4.1.1 Disposal container impact performance

A selection of impact accident condition faults have been defined for the SF / HLW disposal containers. The Variant 2 container remains robust in all accident scenarios. The Variant 1 container remains robust in all but one scenario, which is predicted to cause a failure.

Impact scenarios that the SF / HLW disposal container must withstand were defined from a HAZOP study (see [37]). The requirement on disposal containers under impact accident conditions is to maintain complete containment. In all scenarios the Variant 2 Disposal Container fulfils this requirement. Variant 1 is thought likely to lose containment in one scenario where it topples sideways onto an aggressive feature, impacting near the lifting feature [37]. The analysis suggests that the nature of the fault may mean it requires designing out of the GDF so the fault cannot happen, or significant design modifications to the disposal container will be required.

4.1.2 Disposal Container Transport Container impact performance

Modelling work has been performed on the conceptual DCTC design for the defined impact accident scenarios. Further design work remains, relating to the lid retention system of the container in a 9 m drop with the package's centre of gravity over its lid end.

Due to the relatively high weight of the disposal container in relation to the unloaded DCTC, its shock absorbers are intentionally designed to be larger than typically found on Type B irradiated fuel transport packages of similar mass.

The impact performance of the DCTC during a 9 m drop onto an unyielding surface has been considered for four drop orientations. In the vertical drop onto the base end shock absorber and the horizontal drop onto the package side, the lid-body seal gaps are small and the stresses in the bolts of the lids and shock absorber are low. Two drop orientations (centre of gravity over the lid end shock absorber edge and vertical drop onto the lid shock absorber), require further development work as gaps between the lids and body develop. A retention system could be designed to restrain the inner lid and package internals. The analysis shows that the design of the DCTC to satisfy the requirements of the IAEA Transport Regulations is challenging but not unattainable.

4.1.3 Conceptualisation of an impact accident

On impact, solid metals local to the point of contact with the target generally deform by 'solid metal flow' and, away from the local area, the container would deflect, buckle and fold. Under impact loading, grout based materials generally crush in the vicinity of the impact, spreading cracks into the rest of the structure. As the material is crushed, grout particulates are generated. It is required that, on impact, the release from packages should be minimised. Releases should be progressive and display no cliff-edge effects. For packages that have unencapsulated contents, minimised release and avoidance of cliff edges may be demonstrated through use of a robust container.

Regardless of specific package design or impact scenario, impact behaviour can be understood as follows. On impact, a waste package would be compressed against a target by its own inertia. In waste containers that are made of steel, under this loading solid metals local to the point of contact with the target generally deform by 'solid metal flow' and, away from the local area, the container would deflect, buckle and fold. The mode of deformation will depend on the thickness of the material, the mass of the package, the velocity of the impact and the support provided to the waste container by the wasteform.

In most waste packages the lid is connected to the body by bolts and this interface is often the part of the waste package that is most susceptible to being breached due to the deformations or loadings associated with an impact.

For UILW packages, the waste container's metal skin and flanges will generally buckle, fold and bend. As the structure deforms, the material in the deformed areas will be subjected to forces of tension, compression and shear, which can result locally in very high strains. The stainless steel materials typically used to manufacture UILW containers are generally extremely ductile materials and would be expected to maintain their integrity under the levels of strain in the impact scenarios, unless there is a significant step-change in thickness within the structure in the deformed areas. We advocate good design for the waste containers to minimise tearing of the outer containment [66], for example, by moving welds away from high-stress areas, tapering changes in thickness and choosing materials that are ductile under all impact conditions so that, should a small tear be initiated, any breach will be very local to the impact site.

Under impact loading, grout based materials (including capping grout, cement-encapsulated wasteforms, the plain-grout annulus in some UILW waste packages, concrete shielding in some waste packages, and the concrete structure in some other packages) generally crush in the vicinity of the impact, spreading cracks into the rest of the structure. As the material is crushed, grout particulates are generated. When a cement encapsulated wasteform crushes, the particles generated would carry with them some of the radioactivity from the waste and, if they are released from the waste package, they could contribute to dose through inhalation, ingestion (directly or through the food chain) and external exposure.

It is required that, on impact, the release from packages of encapsulated wastes should be minimised and there should be no release from packages that have unencapsulated contents. For all packages, it is required that the behaviour should be predictable in that there should be no cliff-edge in behaviour over the range of drop heights in any drop orientation and the behaviour must be robust to any uncertainties, such as those associated with the ageing of specific package features. Through careful design, waste packages will perform well under impact accident conditions and have minimal or no release, even when they suffer a large deformation.

There are two key strategies to reduce particulate release from packages containing encapsulated wasteforms:

- minimising the extent to which the wasteform crushes, thereby minimising the creation of particulates that would be available for release. Some designs include a layer of plain grout between the waste container and the wasteform to increase the distance particles must travel to the surface of the container, reducing the volume of the active wasteform that would be crushed and reducing the generation of particulates potentially incorporating radioactive material.
- improving the integrity of the waste container, especially the bolted lid-to-body interface that is the most vulnerable area in most waste packages. Strategies to protect the lid-to-body bolts during impacts include:
    - placing the bolt heads in recesses in the lid flange to avoid contact with the target
    - using body flange spigots to resist the shear displacement between the lid flange and the body flange
    - making bolts from stainless or high tensile steel material (with an inherently higher energy absorbing capacity)
    - using larger bolts
    - reducing the thickness of the lid so that the loading on the lid bolts due to lid 'prying' is reduced
    - reducing the size of the lid so that the bolted interface is smaller and likely to be further from the impact site.

While packages with cement encapsulated wastes are typically designed to allow large deformation during impact, packages for unencapsulated contents are typically designed either for minimal deflection, such that the lid-body interfaces suffer minimal distortion (as in typical RSC packages), or the lid-body interface is welded with high quality welding instead of bolting such that distortion can be more easily accommodated without the risk of a breach in containment (as in HHGW disposal containers). For the former arrangement, a thick-walled structure is normally adopted in order to achieve minimal deflection. The structure is designed to crush locally at the impact point and the thickness of the structure is chosen such that the stresses during impact are sufficiently low that integrity is not compromised. Similarly, the lid-body interface system is designed such that any displacement between the lid and the body can be accommodated by the bolts without causing the stress to exceed specific limits that maintain their integrity. For the latter arrangement, the whole containment, including the welds, will typically be designed such that the plastic strains are sufficiently low so that there is no risk of a tear causing a breach in containment.

Joint guidance by UK regulators to licensees [45] on the management of higher activity waste on nuclear licensed sites recommends that a minimum package lifetime of 150 years should be set for design purposes. In any case, it is apparent from the GDF transport schedule [9] that many packages will have been stored for several decades prior to receipt at the GDF. The effect of ageing becomes more of an issue as the lifetime of the waste package progresses. Our initial understanding of the mechanisms for ageing is that the waste containers are unlikely to be affected significantly during the 50-100 year interim storage period at waste packager sites or during GDF operations, with a very low general corrosion rate of 0.01 µm per year (best estimate) for stainless steel packages [2]. Furthermore, it is not thought that there are any degradation processes that are likely to lead to detrimental ageing of cementitious materials over the timescales considered [67]. Should a package contain more than a negligible quantity of free liquids, justification is likely to be required as part of the Disposability Assessment as to its effect on package performance. There is some uncertainty, however, as to the effect of ageing on the way in which radionuclides are retained within cementitious material, which may alter impact performance [68]. Further research is being carried out to quantify the mechanical performance of aged waste packages. This includes experimental studies of aged test packages that have been stored in known conditions and the laying down of new samples under controlled conditions for future experimentation (See [10] task 911).

4.2 Approach to determining waste package performance

Extensive physical drop testing has been performed on waste containers. Even so, comprehensive physical testing of all drop and package permutations would be prohibitively expensive. Thus, Finite Element Analysis (FEA) has been extensively used to extend the knowledge base of expected package performance.

The RF, as previously noted, is used to estimate the amount of radioactive material that could enter the immediate environment in the event that a waste package is involved in an accident. The foundation of our understanding of the impact performance and the release of radioactivity from waste packages in accident impact scenarios has come from extensive physical drop testing in the 1980s and 1990s of waste containers filled with simulated wasteforms. With the advance in computational techniques in the 1990s and 2000s, extensive computational analyses have also been carried out to further this understanding.

Waste containers are used for a variety of wasteforms that have been conditioned or encapsulated in a number of different ways. It is not feasible to test the performance of each of these waste package types in a range of impact scenarios (such as different orientations and different drop heights) and so computational techniques are also used to extend the results of physical tests to other wasteforms, accident targets and orientations. The tests that have been undertaken are discussed in Section 4.2.1 and the computational techniques used are described in Section 4.2.2.

4.2.1 Drop testing

Waste containers are filled with a representative simulant wasteform; they are then released from a defined drop height and any particulate release collected and the size distribution analysed in order to determine the extent and nature of the release. It was concluded that these waste packages show progressive damage with impact energy for increasing drop heights.

The impact performance of waste packages has historically been demonstrated by physical drop testing. Waste containers are filled with a representative simulant wasteform, released from a defined drop height and particulate release measured after the impact test. Nirex carried out three major series of drop tests in the 1980s and 1990s.

The first drop tests were carried out between 1987 and 1988 [69]. A total of eleven tests in various orientations and heights were conducted on five 500 litre drum designs, each with representative design features and containing selected wasteform types. Deceleration and knockback were measured, as well as the particle size distribution of the crushed wasteform. It was concluded that the steel containers were capable of sustaining large deformations during an impact with no, or minimal, breaching. The extent of knockback was influenced by the crushing characteristics of the contents.

The second series of tests was carried out between 1991 and 1993 as part of a larger research project on activity release from ILW waste packages under impact accident conditions [70]. The objective of that work was to evaluate the important parameters for calculation of the consequences of impacts involving UILW packages. The work included:

- nine drop tests of 500 litre drums filled with four different types of inactive simulated wasteform. Seven drops were carried out with a horizontal orientation onto a punch. The other drops used either a lid-edge or a base-edge orientation onto a flat unyielding target. All the drops were from 25 m. Deceleration, knockback and particulate release were measured. A number of the drums were also skinned (the outer waste container was removed) and the loose material collected and analysed to give data on the quantity and distribution of particulate.
- two drop tests using two prototype 3 cubic metre box waste containers filled with inactive wasteform simulants showed that these waste packages can absorb significant impact energy without catastrophic failure of the waste container. Some of the bolts failed, leading to an opening in the lid to body interface. The amount of material released, box deformation and deceleration were all measured.
- eighty wasteform break-up tests of eighth-scale samples of ten types of inactive simulant wasteforms.
- small-scale break-up tests of eighth-scale samples of active wasteforms.
- development and benchmarking of three dimensional FE impact analysis models of 500 litre drum waste packages.
- wind tunnel testing to investigate the resuspension and spread of released particulate.

The third series of tests was carried out between 1998 and 1999 [71]. This included drop tests of:

- 500 litre drums with homogeneous contents
- 500 litre drums with a grout annulus that provides extra protection to the waste
- 500 litre drums with three different lid-design variants
- super-compacted waste pucks of hard and soft wastes
- eighth-scale clad and unclad samples of homogeneous wasteform simulants
- fifth-scale clad samples of heterogeneous wasteform simulants.

It was concluded that these waste packages show progressive damage with impact energy for increasing drop heights (that is, no cliff-edge effects were observed). Several lid-to-body connections were tested and a spigot on the body flange was shown to exhibit superior performance. Good information was provided from the puck tests and small-scale tests.

As well as these three series of tests, Nirex also carried out stand-alone drop-test programmes for prototype 3 cubic metre boxes [72].

In the tests where there was a breach in the containment that resulted in a release of the contents, any material ejected from the waste package was collected and sized in order to appropriately characterise the released particulate material. Drop tests were conducted on still days or in an enclosure to ensure that most of the released material was collected for analysis. The range of particulate that is of most interest is the size range that is considered to form airborne particulate (less than 100 µm).

From these full-scale tests and analysis of the results, we have gained a good understanding of the behaviour of waste packages on impact and have built an extensive knowledge base against which the impact performance of any future design of waste package can be benchmarked.

4.2.2 Combined FE modelling with small-scale breakup test approach

Finite element modelling of the behaviour of waste packages during impact events can simulate structural behaviour, such as deformations, stresses, strains and material failure, but it cannot easily simulate the particulate breakup of wasteforms or predict release fractions. This can be done by combining the modelling with break-up tests of the wasteform to obtain the relationship of energy input to the mass of particulates generated.

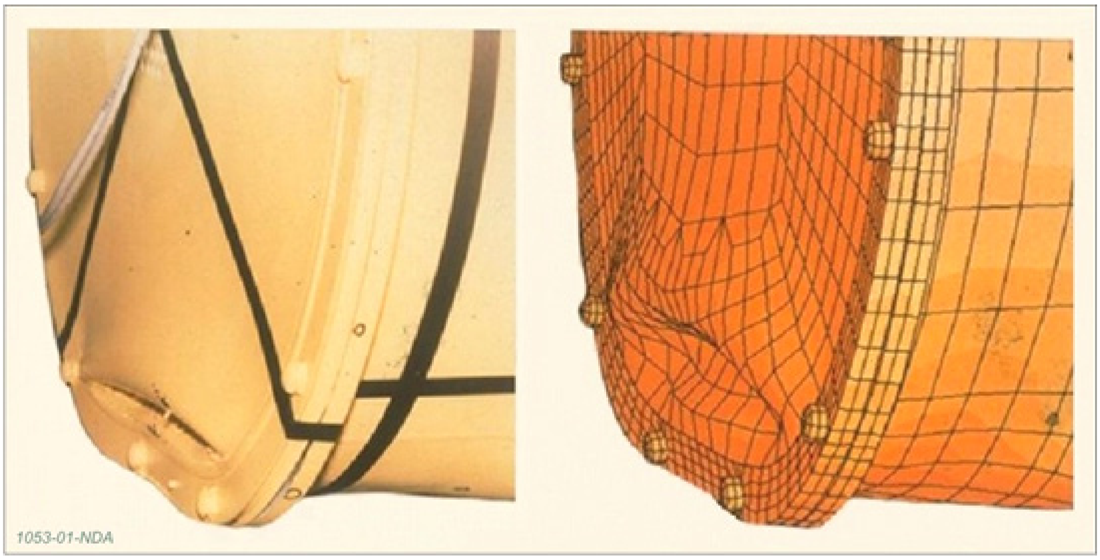
Given the number of possible combinations of package, velocity, orientation and target, it is not feasible to conduct drop tests for each possible scenario. RWM has been at the forefront in employing the FE technique to simulate the behaviour of waste packages during impact events for over 20 years. While this technique is good for the simulation of structural behaviour, such as deformations, stresses, strains and material failure, it cannot easily simulate the particulate break-up of wasteforms or predict release fractions. Therefore, we have developed an approach that combines FE simulation with wasteform break-up tests to determine waste package impact performance in terms of particulate generation and release for waste packages with encapsulated wasteforms [73].

FE simulation

Finite element analysis is widely used across industry to predict the performance of components under dynamic, as well as static, stresses. RWM is at the forefront of the use of FE models to predict waste package impact performance.

For over 20 years, non-linear explicit transient FE models have been used to simulate the behaviour of waste packages during impact events. RWM has been at the forefront of employing this technique in the analysis of waste packages. With continuous development, benchmarking against drop tests and component level benchmarking, we have developed a unique track record and expertise in employing this tool to robustly simulate the impact performance of waste packages. Over the years, FE analyses have been carried out to simulate the impact performance of a range of waste package types, including many specific waste package designs under a wide range of accident scenarios. The package deformations shown in Figure 20 all came from analyses using this technique and represent a small selection from the extensive programme that we have carried out. Figure 27 shows a comparison of modelled waste package behaviour against the actual deformation that results from physical testing, which shows excellent agreement.

Figure 27: Comparison of actual (left) and modelled (right) deformation of a 500 litre drum following a 25 m side drop



Wasteform small-scale break-up tests

Small-scale wasteform break-up tests using simulant wasteforms have elucidated the relationship between impact energy and the mass distribution of particulates released.

Within the three series of waste package impact performance research discussed in Section 4.2.1, small-scale wasteform break-up tests using active and simulant wasteforms were also carried out. In addition, a standalone series of break-up tests was conducted in the 2000s [74] to further study the break-up behaviour of wasteforms.

Two alternative experimental regimes were developed and used:

- Drop-weight tests, where a sample of simulant wasteform is placed on an anvil and a steel impactor is dropped from the required drop height. The particle size distribution of the break-up is then measured by a combination of sieving and laser diffractometry analysis.
- Pressure-gun tests, where an airgun propels a sample of simulant wasteform into a steel target. Particulates are separated from the larger fragments by a vertical airflow and these particles are collected and analysed using separators and fine particle classifiers.

Both methods allow the break-up characteristics of wasteforms to be analysed, particularly the relationship between impact energy and the mass distribution of particulates released.

We are carrying out research that may be used to further refine these data. It is thought that grout, which is constrained within a container and crushed under impact, may not always end up as particulate available for release. When drums from drop tests are skinned, instead of large amounts of particulate wasteform, there is a wasteform that appears to have flowed into the deformed knocked-back geometry of the waste package and then solidified. Therefore, there is an uncertainty (with a potentially significant pessimism) over how wasteforms behave on impact – they either break up and shatter or flow and then re-solidify. We will attempt to identify the mechanism(s) that cause the latter behaviour and aim to quantify its effect by analysing a series of small-scale drop tests of grout within thin-walled containers. We aim to reduce any inherent conservatism in the combined approach described below, which currently uses the break-up data from impact gun tests.

The combined approach

RWM has developed a methodology for combining impact test data with finite element analysis in order to determine release fractions for an extensive range of ILW wasteforms.

The combined FE analysis and break-up testing approach to assessing waste package behaviour (detailed in Box 2) is based on three key elements:

- development of an FE model and carrying out a FE simulation of a waste package for the impact scenario
- taking the FE simulation's prediction of energy absorbed by the wasteform and using the break-up characteristics of the wasteform from wasteform break-up tests to predict the quantity and size range of particulates that would be generated during the impact
- using the FE simulation's prediction of the integrity of the waste package's containment to estimate the fraction of the generated particulates that could be released from the waste container.

Box 2 The steps comprising the FE analysis and break-up testing approach to assessing waste package behaviour

1. Develop a detailed FE model of the waste package to established good practice. In the model, the solid mesh of the wasteform should be organised into many individual volumes, each volume having a similar size to a break-up test specimen and each volume consisting of a group of solid elements from which the energy absorption can be obtained directly from the FE analysis.

2. Run the FE model through to completion. Perform checks to ensure the model behaved in a realistic manner.

3. In parallel with the FE simulation, conduct break-up tests of the wasteform.

4. From the break-up tests, obtain the relationship of energy input to the mass of particulates generated.

5. Obtain from the FE analysis the energy absorbed by each individual volume of the wasteform in the FE model. Calculate the mass of particulates smaller than the relevant size that would be generated in each individual volume (that is, the release fraction from the wasteform per individual volume) based on the energy-mass of particulate relationship obtained from the break-up tests and the energy absorbed from the FE analysis.

6. For each individual volume, estimate the fraction of the generated particulates (from step 5) that could be released from the waste container, taking account of the size of any openings, the distance of particulate generation to the openings, the presence of blockages between the particulates and the openings, and any gross change in the volume of the waste package that could drive the particulates out of the waste package through the openings.

7. Calculate the total amount of particulates that could be released from the waste package by summing the quantity of particulates that would be released from the individual volumes.

8. Using the total waste package contents and the particulate release, calculate the RF from the package.

Research is underway to better understand the complex mechanisms that affect the fraction of the particulates generated that could be released. Until the work is complete, conservative assumptions will continue to be used in waste package assessments to estimate the fraction of the generated particulates that would be released. For example, when there is any opening and the particulates generated are within one package diameter distance (for cylindrical packages) from the opening, all the generated particulates are considered to be released unless there is an un-breached anti-floatation plate or an inner lid in between the generated particulates and the opening, in which case the generated particulates will not be released.

In the absence of a detailed understanding of the complex mechanisms that affect the fraction of the generated particulates that could be released, a ‘coarse’ version of the methodology has also been developed. Instead of dividing the wasteform into individual volumes that represent the size of a break-up test specimen, and obtaining the energy absorbed and quantity of particulates generated for each of these individual volumes, the wasteform is treated as a whole; energy absorbed by the whole wasteform is obtained from the analysis and the mass of particulate generated is calculated for the whole wasteform (to give the release fraction from the wasteform). Based on whether there is any opening in the containment, the presence of an anti-flotation plate or an inner lid, and the distance of the particulates from the opening, a conservative fraction (a 'containment factor') is used to estimate the amount of the generated particulates that could be released to obtain a conservative 'release fraction from the package'.

Validation of the combined FE break-up test approach

In order to validate RWM's combined finite element / break-up test approach, the behaviour of the various package components (wasteform, container and lid-bolts) has been extensively validated via a series of benchmarking exercises, as has the performance of the whole package. The validations have shown that the FE-break-up test approach is robust and that the predictions from the approach are consistently conservative.

The capability of FE modelling to accurately simulate the behaviour of a waste package on impact has been demonstrated and continuously improved by successive benchmarking against drop tests over many years.

The validation process also included 'component level' benchmarking, validating the modelling of key components in waste packages such as the wasteform and the lid bolts against detailed and extensive mechanical tests of these components.

The majority of waste containers and their furniture are made from steel, whether it is austenitic stainless steel, carbon steel or duplex steel. The stress-strain behaviour of these steel materials is well understood and the methodology to model the behaviour reliably is well established.

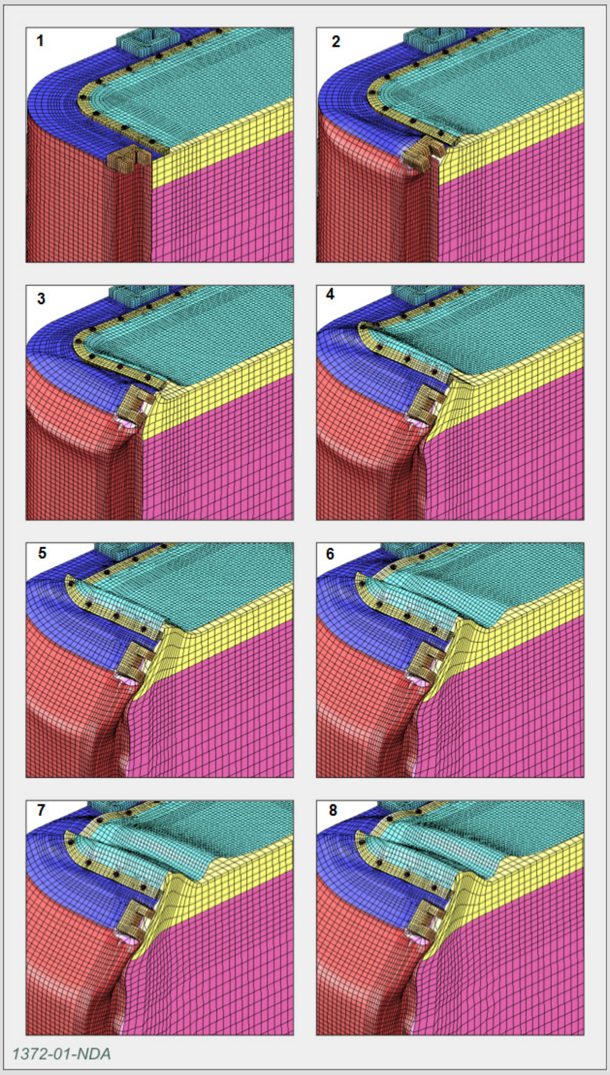
The stress strain behaviour of cementitious materials (such as plain grout in the capping layer of waste packages, cement encapsulated wasteforms, and the concrete wall of certain waste packages) in impact scenarios is less well understood, but accurate modelling of these materials is key to reliable modelling of waste packages. Therefore, we have carried out extensive material testing to characterise their behaviour and benchmarked state-of-the-art mathematical models in the FE technique to simulate their behaviour. This work is described in Box 3.

Although the stress-strain behaviour of steels is well understood and the methodology for modelling their behaviour well established, the large deformation dynamic behaviour of stainless steel bolts is not well characterised. Since the bolted interface between the lid and the body of waste containers is often the most vulnerable area in the waste container in impact scenarios accurate understanding of bolt behaviour and reliable modelling are crucial to obtaining an accurate simulation of waste package behaviour, especially in the simulation of the integrity of the lid-body interface. Therefore, we have carried out extensive testing of stainless steel bolts and benchmarked state-of-the-art mathematical FE models against this testing. These bolt models can then be used in the modelling of waste packages. This work is described in Box 4.

Box 3 ‘Component level’ benchmarking of the behaviour of cementitious materials on impact [75,76,77,78]

In ILW packages, the contents (for example, a cement-encapsulated wasteform, grout annulus and concrete lining) absorb a significant proportion of the impact energy. The figure below shows the deformation of a 3 cubic metre box following a drop onto a flat unyielding target with the box’s centre of gravity over its lid edge. The pink area is the grouted wasteform and the yellow area is the capping grout, both of which deform as they absorb energy from the impact and are crushed. A robust modelling of this energy absorption behaviour for these materials is crucial to the reliability of the whole analysis model.

Figure 28: Deformation of a 3 cubic metre box following a drop onto a flat unyielding target

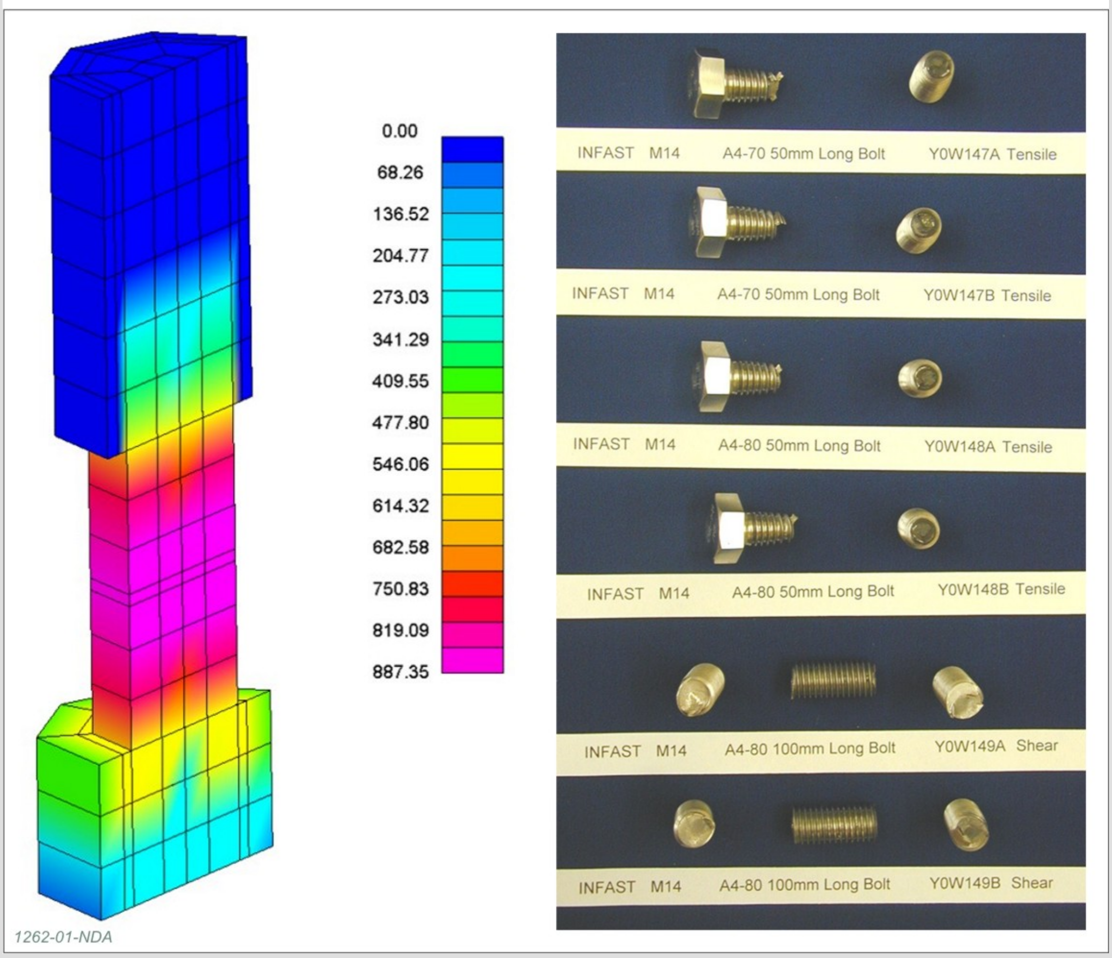


In order to understand the behaviour of cementitious materials in impact scenarios, and to validate a state-of-the-art material model for such materials, two extensive mechanical test programmes, one for plain grout material and one for concrete, were carried out. The first programme consisted of a total of almost 160 tests. These included static and dynamic uni-axial unconfined compressive and tensile tests, confined uni-axial compressive tests and tri-axial compressive tests with a range of different confining pressures. The tests were performed on samples of a 3:1 pulverised fuel ash (PFA)/Ordinary Portland Cement (OPC) cement grout with a water/cement ratio of 0.42, and a 3:1 blast furnace slag (BFS)/OPC cement grout with a water/cement ratio of 0.35. The behaviour of the grout was studied and the model was benchmarked and calibrated against these tests. The second series of tests was carried out on C50 grade concrete without superplasticisers. A total of about 80 tests were carried out and the material behaviour was studied.

Box 4 'Component level' benchmarking of bolt behaviour in impacts [79]

In most waste package designs the bolted lid-to-body connection is the weakest part of the containment and the bolts are the components most vulnerable to failure. Therefore, the behaviour of bolts is an important factor in the integrity of the containment and the size of any breach through which particles could be released. The bolts at the lid-to-body interface experience extreme stresses and strains in maintaining the lid-to-body connection during an impact. Understanding this behaviour is vital to providing a robust FE model of waste packages. An extensive study carried out between 2000 and 2001 included a bolt-testing programme of tensile and shear tests on a total of 88 bolts, representing four grades of stainless steel materials, three thread sizes and two geometries at three strain rates. Some of these bolts are shown on the right below. FE models of the bolts were developed and were benchmarked against these tests. The example below left shows a model of a tensile test on an M16 thread bolt prior to failure, clearly showing the point of maximum stress to correspond to the point of failure in physical tests. The benchmarked bolt model has since been employed in a range of impact models of 500 litre drums and 3 cubic metre boxes.

Figure 29: A model of a tensile test on an M16 thread bolt prior to failure (left), alongside tested bolts used for benchmarking of the model (right).



In addition to benchmarking FE models against drop tests and benchmarking individual components against tests, we have also validated the whole FE-breakup test approach against drop tests to ensure that it is robust and reliable [73,80,81]. The validation was carried out in two stages:

Stage 1 Validation of the FE simulation of the waste package against drop tests, by comparing the deformation behaviour, knockback behaviour and deceleration characteristics from the analysis against the tests.

Stage 2 Validation of the FE-breakup methodology by (i) calculating the breakup and comparing this with the measured breakup from the drop tests, and (ii) calculating the release and comparing this with the measured release from the drop tests.

The validations have shown that the FE-breakup test approach is robust and that the predictions from the approach are consistently conservative.

5 Waste package fire performance

This section of the report discusses our current understanding of how waste packages perform during a fire or under extreme thermal conditions. We summarise the experimental testing and computer modelling that has been carried out. We begin with a discussion of potential package performance in Section 5.1.

Many waste packages that are today in interim stores, have a current LoC. Its production will have included an evaluation of the accident performance of the proposed waste packages using the methodologies outlined in Section 5.2:

- FE modelling, utilising small-scale active furnace test data
- analogy to other waste package performance.

5.1 Potential waste package behaviour

When exposed to fire the external surface of a waste package will heat up. This heat is then transferred inward to the rest of the waste package. The heat transfer is usually dominated by the thermal diffusivity of the package contents. Heating of the wasteform may cause radionuclides to be released as gases, or to be carried by steam.

When a waste package is involved in a fire accident, such as those discussed in Section 3, the waste package absorbs heat. It is usual to assume that a waste package is fully engulfed in the flames.

The waste container is designed to provide containment of the waste, but also provides a barrier to air ingress sufficient to prevent internal combustion of the waste. When exposed to a fire, the external surface of the waste package would heat up. This heat would then be transferred inward to the rest of the waste package. The heat transfer is usually dominated by thermal diffusivity, although other heat transfer processes (such as thermal radiation) may also contribute. Thermal diffusivity combines the thermal conductivity with the volumetric heat capacity and gives a good indication of a material's response to heating. For example, steels with a high thermal diffusivity rapidly adjust their temperature to that of the surroundings. Waste packages are designed to minimise the heating of the wasteform, for example, by having a low overall thermal diffusivity. As a consequence, the centre of the waste package may not experience its maximum temperature until several hours after the fire has been extinguished.

The principal concern about waste package performance in the event of a fire is that, for packages that are not designed to be airtight, such as the disposal container, the heating of the wasteform could cause radionuclides to be released. There are various processes by which this might occur:

- some solids may react with air inside the waste package to form a gas, which may then be expelled from the package as the gas inside the container expands due to the increased temperature
- some solids may be volatile and, when heated, may change phase to a gas (either by vaporisation or via pyrolysis), which could then escape from the waste package
- the wasteform may contain water (for example, bound into cementitious grout) which, when heated, produces steam. The steam may escape from the waste package, possibly carrying with it some of the radioactive waste.

For assessment of accident consequences involving ILW and SILW packages it is always assumed that the volatilised radionuclides are released. This occurs via an engineered vent in the package, through small gaps in the lid-body interface, or via porosity in the container. High Heat Generating Waste packages are designed to withstand the increase in internal pressure generated from heating as a result of a fire fault, as such they are assumed to have zero release.

The effect of ageing becomes more of an issue as the lifetime of the ILW and SILW packages progresses. Our initial understanding of the mechanisms for ageing is that the waste containers are unlikely to be affected significantly during interim storage at waste packager sites or during GDF operations, with a very low general corrosion rate of 0.01 μm per year [2]. Corrosion can lead to the evolution of hydrogen, which could, in certain circumstances lead to the possibility of a hydrogen deflagration. This possibility is noted for future considered within the Operational Safety Case.

It is not thought that there are any factors that are likely to lead to detrimental ageing of the cementitious materials over the 50-100 year timescales for interim storage at waste packager sites or during GDF operations. However, there is some uncertainty as to the effect of ageing on the way in which radionuclides are retained within the cementitious material, which may alter fire performance [68]. Work is underway defining the research strategy to investigate this effect and to locate existing historical materials that may be available for experimentation. It is expected that the future strategy will include the laying down of new samples under controlled conditions for future experimentation (see [10] tasks 1010 and 1011).

5.1.1 ILW packages

In a thin-walled UILW package, it is the thermal properties of the materials inside the container that limit the heat reaching the centre of the waste package. Cementitious grout has been shown to be an excellent material for limiting the heat reaching the waste if the package is exposed to a fire. Gases and steam may be generated, which can escape through the installed vent.

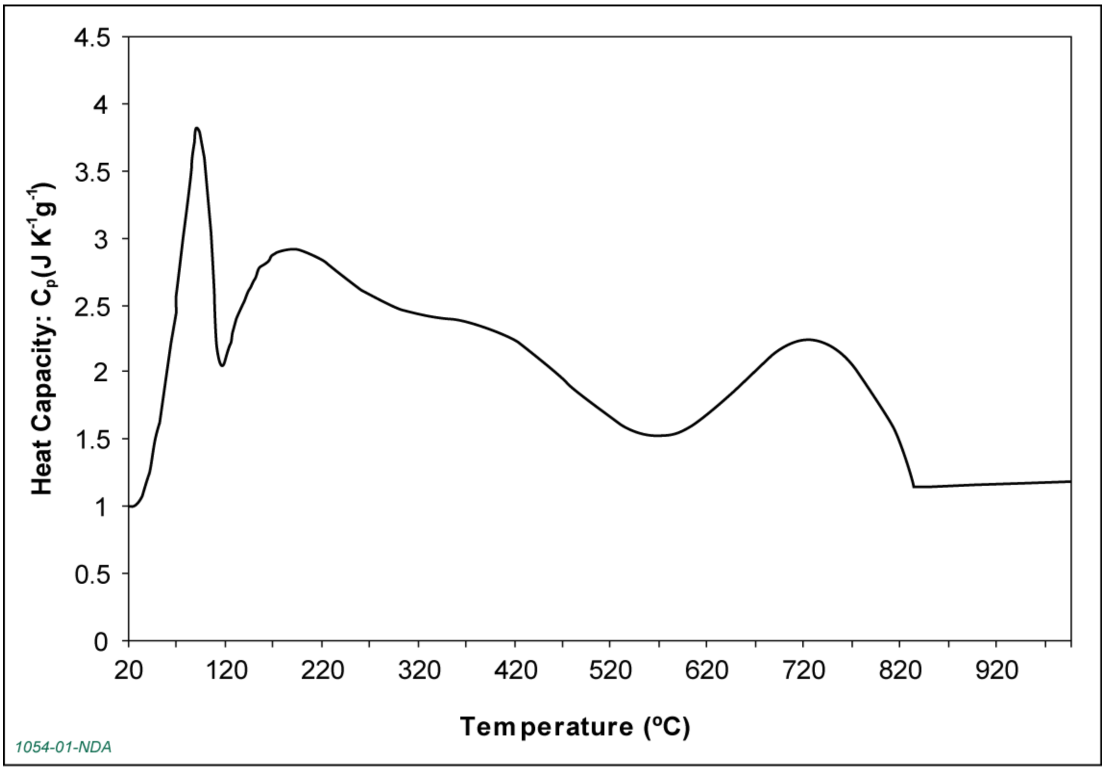
ILW packages are generally unshielded and the wasteform is contained within a relatively thin-walled stainless steel drum or box. These ILW containers are designed primarily to provide containment and handling features. The ILW containers are fabricated from corrosion-resistant steels, but these materials typically have a low thermal capacity and would therefore heat up rapidly when engulfed in a fire. Therefore, it is the thermal properties of the contents within the waste container that provide the fire protection.

Gases and steam may be generated inside the UILW packages when exposed to a fire, over and above the small quantities of gases that may be generated during normal storage. UILW containers, with their relatively thin walls, would not be able to withstand the internal pressurisation caused by these gases but are normally fitted with an engineered vent. The engineered vent would minimise the release of particles of radioactive waste with the escaping steam or gas.

It is noted above that, in a UILW package, it is the thermal properties of the materials inside the stainless steel waste container that limit the heat reaching the centre of the waste package. Most waste packages contain cementitious grout. In many waste packages this is used to immobilise the waste (by forming it into a single solid mass). In some packages a cementitious grout is also used to form a lining around a wasteform that is less resistant to higher temperatures; the grout annulus then provides thermal shielding to the wasteform.

Modelling sensitivity work has shown that the thermal performance due to changes in thermal properties (varying each of the above properties in a typical grout by factors down to 0.3 or up to 3.0) is dominated by the thermal conductivity and the specific heat capacity. Changes in density do not play as significant a role in influencing thermal performance because the possible variability in density is much less than the potential variability in thermal conductivity.

Figure 30: Heat capacity variation with temperature for a grouted wasteform



Cementitious grout has been shown, for two reasons, to be an excellent material for limiting the heat reaching the waste if the package is exposed to a fire. Firstly, it has a low thermal diffusivity (a combination of a low thermal conductivity and a high volumetric heat capacity) which, when the grout is dried out by the heat from the fire, reduces further. Secondly, cementitious grout contains a significant amount of water bound inside it which, when heated, is released as steam. Turning water to steam requires a significant amount of heat (called latent heat) and when modelling heat transfer through cementitious grout, this latent heat is usually included as an effective specific heat which has a large peak at around 100°C, the temperature at which most of the steam is generated. Figure 30 clearly shows the 100°C peak for water release from a grouted wasteform, comprising free water and water bound in the cement Calcium-Silicon-Hydrate (CSH) gel (it is this gel that binds a grout together). The broader peaks at progressively higher temperatures correspond to water retained within the CSH gel under differing regimes. It is this low thermal diffusivity that makes cementitious grout an excellent material for preventing the heat from the fire penetrating far into the waste package.

Other encapsulating materials have been used for ILW, including organic resins. Organic resins are very good at immobilising challenging wastes, such as powders, but are not stable at high temperatures, breaking down in the region of 400-500°C. To provide the same level of thermal performance, waste packages using resin often include an outer lining of grout to provide insulation against fire.

Some ILW packages contain irradiated graphite. If this graphite has been irradiated at a relatively low temperature, some of the irradiation energy (called Wigner energy, see Box 5) may still be bound up inside it and would be released if the graphite is heated. Potentially this can lead to a run-away event as increasing the graphite temperature causes the Wigner energy to be released; this, in turn, causes further heating of the graphite. When packaging such graphite, it is important that exposure of the waste package to a fire does not trigger such a run-away energy release. This can be ensured by either annealing the graphite, or by providing the graphite with an outer annulus of cementitious grout (which limits the heat reaching the graphite) and by encapsulating the graphite with sufficient material with a high thermal capacity (such as cementitious grout) so that the temperature rise resulting from any release of Wigner energy is small.

Box 5 Wigner energy

Wigner energy results from the displacement of atoms in a solid by neutron radiation. Any solid can be affected, but it is of most concern in the neutron moderators used in nuclear fission reactors to slow down fast neutrons, particularly graphite.

To create the Wigner effect, neutrons that collide with atoms in a crystal structure must have enough energy to displace them from the lattice. A small number of displaced atoms come to rest outside the symmetrical lines of the lattice and are known as interstitial atoms. Because these atoms are not in the ideal location they have an energy associated with them, much like a ball at the top of a hill has gravitational potential energy. When large numbers of interstitial atoms have accumulated, there is a risk of releasing all of their energy suddenly, creating a temperature spike. Such a release can be initiated by a relatively modest temperature increase, which may then lead to a runaway temperature excursion. It was an excursion such as this that caused the fire at the Windscale Pile 1 reactor in 1957.

Wigner energy can be dissipated by controlled heating (‘annealing’) of the material during which the interstitial atoms realign themselves. (Note, graphite from high temperature reactors does not contain significant Wigner energy as the material is effectively annealed *in situ*.)

In transport, gas generation from waste packages is considered as part of the Disposability Assessment process, ensuring that wastes are not packaged in a form or at a waste loading that might exceed the relevant IAEA Transport Regulations for gas (in terms of any release of gaseous radionuclides, formation of hazardous gas mixtures or pressurisation of the transport container). During the GDF’s operational phase, the gases that need to be managed are mainly flammable (for example, hydrogen), chemotoxic (for example, amines) and radiotoxic (for example, C-14 and Rn-222). Confidence in safety during the operational phase is developed by showing, for example, that the gases formed within the GDF can be managed by ventilation and that the resulting discharges will be less than regulatory limits.

Heating of the waste inside ILW packages may also result in chemical reactions, leading to changes in the wasteform and possibly the generation of flammable gases. Although ILW packages are provided with an engineered vent, this is designed to be too small to enable sufficient air to enter the waste package during normal conditions before an accident for self-sustaining combustion. During a fire accident, the conditions within the waste package will give rise to an increase in water vapour and gas generation, which will provide a positive flow from the interior to the edge of the wasteform and out of the waste container (through the engineered vent or via any penetration sustained in a combined impact / fire accident). This positive gas flow in a fire prevents air ingress through the engineered vent and into the wasteform. Excluding hazardous materials wherever possible [82], and air ingress, from the waste package also serves to minimise the production of flammable gas mixtures inside the waste package. Any content of the waste package which may cause toxic release or self-ignite may require specific underpinning to demonstrate adequate performance during the assessment of disposability for the package.

5.1.2 Disposal containers

In a fire incident involving a disposal container, the temperature rise experienced by the waste is limited by the large mass, and hence thermal capacity, of the waste container. Even if the disposal container were engulfed in the flames of a fire for one hour, the predicted temperature rise experienced by the waste would be relatively modest.

In a number of geological disposal programmes worldwide stainless steel, carbon steel, cast iron, copper, titanium and nickel-based alloys have all been proposed or considered as SF / HLW disposal container materials. Many container designs include an internal insert. Such designs combine the corrosion protection afforded by a suitably durable container material with the mechanical strength, ease of fabrication and cost effectiveness of other materials. These metals are all good conductors of heat. In a disposal container fire accident the heat reaching the waste would not be limited by the conductivity of the materials. Instead, the temperature rise experienced by the waste is limited by the large mass, and hence thermal capacity, of the disposal container. Even if the disposal container were engulfed in the flames of a fire for one hour, the temperature rise experienced by the waste is predicted to remain below approximately 400°C for Variant 1 containers and 480°C for Variant 2 containers [37].

The disposal container will be completely sealed, with no ventilation. The wastes in disposal containers will not contain significant amounts of water and significant quantities of gas will not be generated when they are heated in a fire. In addition, the disposal container will be much stronger than the thin-walled ILW containers. It has been determined that the integrity of both the outer corrosion protection layer and the inner structural insert of both RWM designs would be maintained in the event of a fire; hence no release of radionuclides would occur [37].

In HLW or SF disposal containers, the heat from radioactive decay can also be significant. This heat load is small compared to the heat from the fire, but it will have an effect upon the peak temperature experienced by the waste and is a consideration in assessments of disposal container performance [37].

Disposal container thermal performance

Both the Variant 1 and 2 disposal containers are predicted to satisfy the requirements for performance during fire faults, with no significant temperature gradients in either container design.

The disposal containers have been designed for a wide range of thermal conditions during storage, transport and disposal. Thermal calculations have been carried out on both variants of disposal container for the waste type with the highest decay heat and with a reference case layout scenario appropriate to the container design. For fire accident conditions, the Variant 1 disposal container was modelled subject to an all-engulfing 1000°C fire lasting one hour [37]. The highest temperatures were found to be below 900°C on the outer surface and 400°C in the fuel channels. Estimates have also been made of the temperatures in the fuel pins/HLW and of corresponding internal pressures.

The calculations demonstrate that there will be no significant temperature gradients (which might affect containment) across the walls of the disposal container, either for fire conditions or following deposition. Internal pressures are predicted to be modest, with a maximum predicted pressure of 0.46 MPa during a fire fault, compared to a conservative estimate for container failure of 14 MPa. The temperatures reached by the container's materials are significantly below the relevant melting points. Therefore, the Variant 1 disposal containers clearly satisfy the thermal performance criteria. Calculations were performed using industry standard modelling techniques. It is noted that these are currently theoretical verifications of designs which are still under development; the methods used for calculating these pressures will need to be validated at a later stage in the design process.

For fire accident conditions, the Variant 2 disposal container was also modelled subject to an all-engulfing 1000°C fire lasting one hour. The highest temperatures were found to be below 780°C on the outer surface and 480°C in the fuel channels. Estimates have also been made of the temperatures in the fuel pins/HLW and of corresponding internal pressures.

The calculations demonstrate that there will be no significant temperature gradients (which might affect containment) across the walls of the Variant 2 disposal container design, either for fire conditions or following deposition. Internal pressures are predicted to be modest. The temperatures reached by the containment materials are significantly below the relevant melting points. Therefore, the Variant 2 disposal containers also satisfy the thermal performance criteria.

5.1.3 Disposal Container Transport Container thermal performance

Modelling work has been performed on the conceptual DCTC design for the defined fire accident scenarios. The main focus of this work was the temperature of the lid seals, which were predicted to remain well within tolerable temperature limits.

A preliminary assessment of the thermal response of a new DCTC design under regulatory transport conditions has been performed. With an assumed internal heat loading of 2000 W and a fire duration of 30 minutes at 800°C (as specified within the transport regulations [14]), the maximum temperature experienced at the outer lid seal (where the greatest temperature limitation applies) was calculated as 143°C. This is deemed to be acceptable with a considerable margin, given the performance characteristics of the seal - the seal used remains serviceable when subjected to temperatures of 210°C for periods of 12 hours following one year at 150°C. Therefore, without prejudicing future work, at this early stage it is considered that the temperature of the inner container is unlikely to be significantly higher than its steady state temperature and therefore unlikely to pose an issue for the wastes contained within it.

5.2 Approach to determining waste package performance

Fire tests have been performed on inactive full-scale packages, small-scale simulant packages and small-scale samples. These data are used to validate finite element simulations of full-scale packages.

The RF, as previously noted, is used to estimate the amount of radioactive material that could enter the immediate environment in the event that a waste package is involved in an accident. Our early understanding of fire accident performance was based on physical testing of waste containers filled with simulated wasteforms. It is not practicable to test a full-scale waste package with real activity and so physical testing of scale-models and computational techniques are used to develop our understanding and extend the results of tests to other wasteforms and accident conditions. The tests that have been undertaken (and which led to the understanding of waste package behaviour discussed in Section 5.1), and the computational techniques used to extend the results, are described below.

5.2.1 Experimental testing of full-scale waste packages

A range of inactive simulated generic ILW, immobilised in stainless steel 500 litre drums has undergone full-scale experimental testing. Throughout all the tests the waste container remained in a good condition, even following a fully-engulfing pool fire. There was no evidence of waste container deformation, wasteform combustion, temperature excursions or encapsulant/waste interactions. Sectioning of the wasteforms after the tests revealed generally little damage or cracking.

Full-scale fire tests were first performed on just a few waste packages containing simulated inactive waste. The objective of these tests was to gain a general understanding of the behaviour of different types of waste packages in fire conditions. A range of inactive simulated generic ILW, immobilised in stainless steel 500 litre drums, was subjected to full-scale experimental testing (see Figure 29). A detailed review of the full-scale tests is given in [59], but in summary the work involved two different types of thermal test:

- a furnace test to simulate a fire accident while drums are being transported inside a shielded transport container
- a hydrocarbon pool fire test to simulate a fire during storage or handling of UILW packages underground at the GDF.

The furnace test exposed the simulant full-scale drums to a relatively low temperature (around 300°C) compared to the pool fire (where the flame temperature could be up to 1400°C). In both types of tests the temperature of the drums of inactive simulated waste was monitored using thermocouples and the material released from the waste was analysed to determine the physical and chemical composition of the gas, condensates and particulates. Test durations were varied according to the temperature requirements of the test, with higher temperatures requiring longer heating durations. Tests were performed on the following generic simulated waste types:

- metallic pieces (fuel hulls) encapsulated in a BFS/OPC cementitious grout
- plutonium contaminated material (PCM) encapsulated in an OPC cementitious grout
- ion exchange resins encapsulated in vinyl ester polymer
- magnesium hydroxide sludge encapsulated in a BFS/OPC cementitious grout.

Tests were performed both on undamaged 500 litre drums and a 500 litre drum that had already been subjected to an impact test - (a drop of 10 metres on to a flat rigid target, with the impact on the side of the drum (e. External damage was limited to flattening of the drum in the impact plane about 300mm wide and there was no breach of containment)). Some tests in the furnace were also performed with the vent sealed, so that the rate of pressurisation and the effect upon the wasteform when the pressure was suddenly relieved could be determined.

Throughout all the tests the stainless steel 500 litre drum waste ILW container remained in good condition, even following a fully-engulfing pool fire (Figure 29). There was no evidence of waste container deformation, wasteform combustion, temperature excursions or encapsulant/waste interactions.

Most of the material released from the test drums was steam. The steam release rate was roughly proportional to the wasteform's thermal conductivity and the original water content of the wasteform. The steam release rate from the pool- fire tests was observed to be approximately an order of magnitude greater than from the corresponding furnace tests (possibly due to lower temperatures in the furnace tests which were a- maximum of 700°C).

No particulates were released from any of the unpressurised furnace tests, even from the previously impacted 500 litre drum. However, some particulates were released from the test drum during the pool fire tests due to the higher flow rate of steam.

Sectioning of the wasteforms after the tests revealed generally little damage and cracking (Figure 32). All the wasteforms remained substantially monolithic, even after a prior impact. The Magnox sludge specimen that was subjected to a sudden pressure release suffered more cracking than the others, but otherwise the pressurisation of the 500 litre drum had minimal effect.

It is currently believed that the tests performed on the 500 litre drums described above provide sufficient general understanding of waste container and wasteform performance in a fire that further full-scale tests are unnecessary.

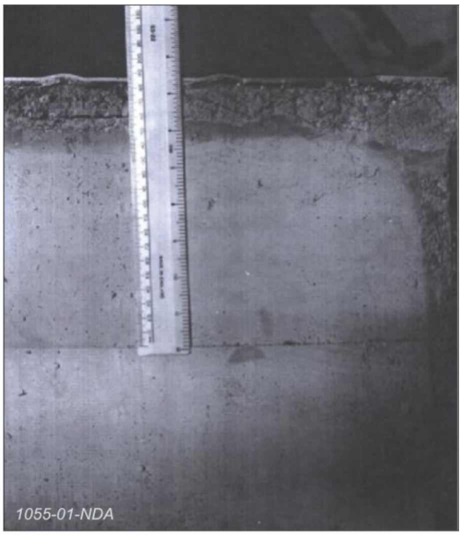
As part of a programme investigating the fire performance of LLW, furnace tests and panel tests (heating from one side) were also performed on full-scale, super-compacted pucks of waste [83] (furnace tests were conducted at waste temperatures of 300°C, 700°C and 1000°C). These pucks were tested 'bare' rather than encapsulated inside a waste package. Four different waste pucks were tested:

- pucks high in paper and low in plastics and rubber
- pucks high in plastics and rubber, low in other materials
- pucks with equal mass fractions of paper, PVC, polythene, rubber and neoprene; and
- pucks of metal plus paper.

The super-compacted pucks of waste were heated up to 700°C in air. The tests included heating the pucks on one side using a panel heater and heating the pucks uniformly within a furnace. The tests showed that the pucks did not burst or expand catastrophically and only the wasteform containing a large proportion of paper exhibited significant swelling. Combustion did not take place within the body of the wasteform. There was degradation at higher temperatures through pyrolysis of the organic material, releasing gases that ignited outside the puck, but this external combustion was not self-sustaining. Therefore, it was concluded that super-compacted LLW has very good resistance to fire [83].

Figure 31: Pool fire test of a 500 litre drum (includes a shield for wind protection)

Figure 32: Sectioned 500 litre drum following a pool fire test



5.2.2 Combined FE modelling with small-scale active furnace test approach

Finite-element modelling of fire accident performance requires as inputs the thermal properties of materials and the RFs from wasteform materials at different temperatures. These RFs can be determined from tests on small-scale samples of actual active wasteforms.

It is not feasible to conduct full-scale tests for each possible scenario. Therefore, we have developed an approach to determining waste package fire-accident performance based on FE computer modelling simulation, in combination with wasteform small-scale active furnace tests.

FE simulation

Computer simulation is used to predict the temperatures reached within specific parts of waste packages involved in fire accidents. The expected releases of radionuclides at elevated temperatures (using data provided by small-scale testing) are then applied to the volume of waste predicted to be at that temperature. The total releases are then summed to give an overall release.

The methodology we have developed for modelling the temperature inside waste packages exposed to a fire is based on the use of FE codes. FE codes have been used widely for several decades for modelling heat transfer and comprise a mature technique. One particular advantage of FE codes is the ability to model heat transfer in complex geometries in both two and three dimensions. FE heat-transfer codes model heat transfer by conduction in solid structures and heat transfer by radiation and convection at the surface of the solid structures.

SF / HLW disposal containers, as described in Section 2.1, can be readily modelled since the heat transfer that occurs during a fire is dominated by conduction through the waste container materials, for which the thermal properties (thermal conductivity, density and specific heat) are well known.

Modelling heat transfer in ILW packages is more challenging because of the presence of cementitious grout. This grout is present in a significant number of ILW packages, either immobilising the waste, forming a protective annulus around it, or forming the container itself. The difficulty in modelling cementitious grout arises because it dries out when heated. This causes the thermal conductivity, density and specific heat to all change rapidly at around 100°C. In addition, as described in Section 5.1.1, the evaporation of the water bound into the grout absorbs heat. If this latent heat is included in the specific heat, the resulting effective specific heat will have some very large peaks, especially at around 100°C. Ensuring that the FE code properly captures these rapid changes in material property has required careful development and testing. These rapid changes also present challenges when the thermal properties are being measured. The generation of steam at around 100°C can lead to erroneous measurements of both thermal conductivity and specific heat.

When defining the thermal conductivity of a cementitious grout, 'undried' and 'dried' values are usually specified, with the change from one to the other occurring over a narrow temperature range around 100°C. It is also worth noting that the grout remains dried when it cools down to below 100°C.

The appropriate values of thermal conductivity are usually obtained from experimental measurements. When considering a wasteform of solid items of waste encapsulated in a cementitious grout, the wasteform is usually modelled as a solid material with appropriate effective thermal properties. The effective thermal conductivity of solid items encapsulated in cementitious grout can be estimated from the known thermal conductivity of the solid waste material and the grout and the proportions of each material in the wasteform.

As described above, the effective specific heat of cementitious grout varies significantly with temperature. Obtaining the effective specific heat at the required resolution from experimental measurements is therefore very challenging. A semi-analytical method has been developed in which the chemical composition of the grout, as a function of increasing temperature, is first calculated [84, 85]. Additively combining the measured specific heat of each component with the latent heat of the water via multiple applications of the Maxwell-Euken equation, a total effective specific heat of the cementitious grout can be determined. For wastes encapsulated in cementitious grout, the specific heat for the waste can be included to obtain the effective specific heat for the wasteform. Waste packagers have proposed using a wide range of different cementitious grout formulations in different waste packages. One advantage of the semi-analytical method that has been developed is that the effective specific heat of these different grout formulations, both fresh and aged, can be derived without difficult experimental measurements being required.

Wasteform small-scale active furnace tests

Heating of small-scale wasteform samples or simulants to a range of specified temperatures allows an understanding of the releases expected from a full-size wasteform that will have a temperature gradient throughout its volume as a result of a fire accident.

It is not practicable to perform fire performance tests on full-scale active waste packages and so tests on small-scale samples of actual active wasteforms have been undertaken to determine RFs. The small-scale samples were contained inside steel cylinders and heated in a furnace. The space at the top of the cylinders was purged with a flow of inert gas (argon) and the out-flowing gases from the tests were put through a condenser, condensate trap and bubblers. The material collected in the condensate trap and bubblers was tested in order to measure the quantities of specific radionuclides released from the wasteform at specific temperatures.

Two test programmes have been performed to date in the UK. In the first series of tests, known as the ARFAC programme [86], examples of actual retrieved wastes were tested. The wasteforms prepared and tested comprised:

- Magnox sludge in a cementitious BFS/OPC grout
- fuel hulls in a cementitious BFS/OPC grout
- plutonium contaminated organic materials
- ion-exchange material immobilised in vinyl ester resin.

The radionuclides measured were Co-60, Sr-90, Ru-106, Cs-137, Pu-239 and Am-241, although not all radionuclides were measured in every case (for example, certain fission product radionuclides are not found typically in ion-exchange materials, so were not included). The radiochemical analyses of solutions and solid starting material were carried out by standard techniques employing γ-ray spectroscopy, α-spectroscopy and β-counting after carrying out any necessary radiochemical separations. Tests were made at wasteform temperatures of 300°C and 1000°C.

In the second series of small-scale tests, known as the ILW fire programme [87], the wastes were generated artificially, rather than being actual retrieved wastes. Each simulant waste material had known quantities of radionuclides applied onto the surface of the waste items prior to immobilisation in a grout or polymer. This meant that the sample contained only those radionuclides of interest and allowed the starting inventory to be controlled, so that the concentrations were known accurately and could be adjusted to a level appropriate for the measurement process. The simulants were doped with radionuclides in the most stable chemical form predicted from thermodynamic calculations of the element in equilibrium with steam and air at 1000°C. Nirex prepared the wasteform simulants so as to be similar to the full-scale tests described in 5.2.1, so that comparisons can be made between the results. The wasteforms comprised:

- ion-exchange material in a cementitious BFS/OPC grout
- fuel hulls in a cementitious BFS/OPC grout
- Magnox sludge, dried and super-compacted
- floc in a cementitious PFA/OPC grout
- metal waste (un-grouted).

The ‘fuel hulls in a cementitious BFS/OPC grout’ wasteform was common to both test series, enabling the consistency of the measurements to be determined.

In addition to the radionuclides measured in the first series of tests, the second series also included measurements for Eu-152 and U-238. The second test series also took account of the fact that much of the wasteform would experience temperatures lower than 300°C. Tests were therefore performed at 150°C, as well as at 300°C and 1000°C.

A detailed review of the full-scale tests is given in [59]. This report also describes measurements of thermal properties that were made on inactive, small-scale samples of various wasteforms.

Of note is that, in general, tested samples that have been doped with radioactive material display greater releases than real waste samples. This is almost certainly because the radioactivity was added to the surface of inactive material (such as fuel hulls), whereas in real waste materials the activity might be much more tightly bound within the waste.

Nirex collated the fire RFs for the nine different wasteforms and radionuclides identified above into a report on recommended fire RFs for use in modelling [88]. The report gives radionuclide RFs for each of six volatility groups[6] as the temperature increases. These RF data can be combined with the temperature distribution from the fire model results to provide a prediction of the release from a waste package.

5.2.3 Details of the combined approach

In conservatively calculating the RF, the following assumptions are made:

- the release is a function of the peak temperature experienced by each part of the wasteform
- where limited modelling has been carried out it is assumed that the entire wasteform experiences the same temperature as the inside edge of the container
- the release is assumed to be independent of the chemical form of each element.

Small, laboratory-scale tests have been performed on a few representative wasteforms. These wasteforms contained a limited number of the more important active radionuclides. Each wasteform was heated and the release of radionuclides measured, from which RFs were derived. These small-scale wasteform tests are described in more detail in Section 5.1. The wasteform RFs for radionuclides not included in the tests have been estimated based on the known volatility and RF data for the few radionuclides tested in the small-scale tests. Tables of recommended RFs for different types of wasteform have been published [88].

In order to assess the release of radionuclides from a specific waste package in the event of a fire the temperature distribution across the waste package during the fire is first derived by numerical modelling. Then, the expected release of radionuclides from the waste package is calculated from the peak temperature experienced by each part (finite element) of the wasteform, the radionuclide inventory of the waste package and the recommended RFs.

To make the calculation of the release of radionuclides practicable, a number of simplifying assumptions have been made:

- based on computer modelling, it is conservatively assumed that the release is a function of the peak temperature experienced by each part of the wasteform, irrespective of how long the peak temperature is sustained, or how far that part of the wasteform is away from openings in the waste container (that is, once activity is predicted to be mobile in a finite element, then it is all assumed to be released through openings such as the ILW package lid vent). The calculated release is therefore only time dependent on the heating time of the package and the length of time for which measurements were taken of the small scale samples (this varies according to the experimental specifics, but is often an hour at peak temperature, plus the time taken to reach this temperature. Some samples in future planned tests are to be heated for 24 hours to investigate possible longer-term releases (see [10] task 1006).
- some waste package designs are in their early stages of development and only limited computer modelling has been conducted to indicate the expected temperatures at the inside edges of the waste container. For these waste packages we assume that the RFs are the same for the entire wasteform based on this maximum temperature. Therefore the wasteform at the centre of the waste package is pessimistically assumed to produce the same release as the wasteform at the

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[6] The volatility groups (I to VI) are described later in Section 5.3.3 and are presented in Table 4.

edge. This conservatism may lead to a large overestimation of the released activity. Work is underway to remove this conservatism (see [10] tasks 946, 947, and 948).

- the release is assumed to be independent of the chemical form of each element (for example, the same RF applies to both carbon in organic material and to graphite) as the small scale measurements to measure release fractions have mainly used simulant wasteform materials doped with only one chemical form of each radionuclide.

5.3 Further small-scale active furnace tests

Further release fraction data for specific radionuclides (H-3, C-14, Cl-36, Se-79, Sn-121m, I-129 and Cs-137) are being sought. This is expected to help reduce pessimisms inherent in the current modelling approach.

Further research using small-scale active furnace tests is under way (see [10] task 946). The aim of this work is to reduce uncertainties and pessimisms in the currently available data.

The function of the active furnace tests and associated experimental strategy is to provide accurate and robust release fraction data for a range of radionuclides and wasteforms under simulated fire conditions.

The range of radionuclides to be studied has been expanded compared to previous work to include three of the volatility group I radionuclides (see Table 4 in Section 5.3.3) that are commonly found in wastes: radioactive hydrogen, carbon and chlorine. Currently, a pessimistic assumption is made that all the volatility group I radionuclides will be in a gaseous form in the event of a fire and hence all would be released. This assumption will be replaced with measured RF data. The recommended fire-RF report [88] will be revised and updated. Overall, a range of seven radionuclides (H-3, C-14, Cl-36, Se-79, Sn-121m, I-129 and Cs-137) has been selected based on elements within volatility groups I and II which currently challenge our Operational Safety Case (OSC). H-3, C-14, Cl-36 and Cs-137 have been tested in previous work, so some results may be comparable, whilst Se-79, Sn-121m, I-129 have not previously been tested.

We are investigating two sample types:

- metal in grout, so that we can compare and advance the knowledge from earlier tests on fuel hulls in grout
- graphite in grout, as waste packagers are developing techniques for packaging these reactor wastes.

In the current work radionuclides are split into discrete sets, rather than including all radionuclides in all samples as in previous work. A particular set is then added to a wasteform simulant sample, depending on the tests and temperatures required. This has the advantage of being able to tailor the radionuclide capture and analytical techniques to small groups of radionuclides, which will lead to a significant improvement in the Limit of Detection (LoD). A further advantage is the greater flexibility of being able to conduct more specifically tailored experiments. The three resulting sets of radionuclides being used in the experimental testing programme are:

Set 1: H-3 and C-14

Set 2: Cl-36 and I-129

Set 3: Se-75, Sn-113 and Cs-137.

5.3.1 Test temperatures

Given the low temperatures experienced by much of the wasteform, particularly noting a reduction in fire scenario durations, lower test temperatures are a key feature of the current experimental programme. These will include 50, 80, 95, 120, 150 and 300°C for key radionuclides.

The previous work was carried out in the temperature range 150°C to 1,000°C. It is recognised that, although the specified fire temperature for the OSC is 1,000°C, this high temperature is only relevant to the outer sections of waste packages. The fire durations are also relatively short (0.5 – 1 hour).

A key gap in the information available for modelling is release fractions for the volatility group I radionuclides, particularly at lower temperatures. The lowest temperature used in previous tests was 150°C. The test temperatures for this work will include 50, 80, 95, 120, 150 and 300°C, with fewer test temperatures for the radionuclides expected to be less volatile.

5.3.2 Sample types

The current experimental programme will use the following waste simulants: dosed foil coupons in grout; dosed Magnox sludge in grout; dosed homogenous grouted wasteform; unencapsulated dosed Magnox sludge; and unencapsulated radionuclide solution.

The following sample types were selected for study:

- dosed foil coupons in grout (similar to surface contaminated materials such as fuel hulls)
- dosed Magnox sludge in grout
- dosed homogenous grouted wasteform
- unencapsulated dosed Magnox sludge
- unencapsulated radionuclide solution.

Schematics of the formats to be used for these sample types are shown in Figure 33 to Figure 36.

Figure 33: Schematic of dosed foil coupons in a grout sample

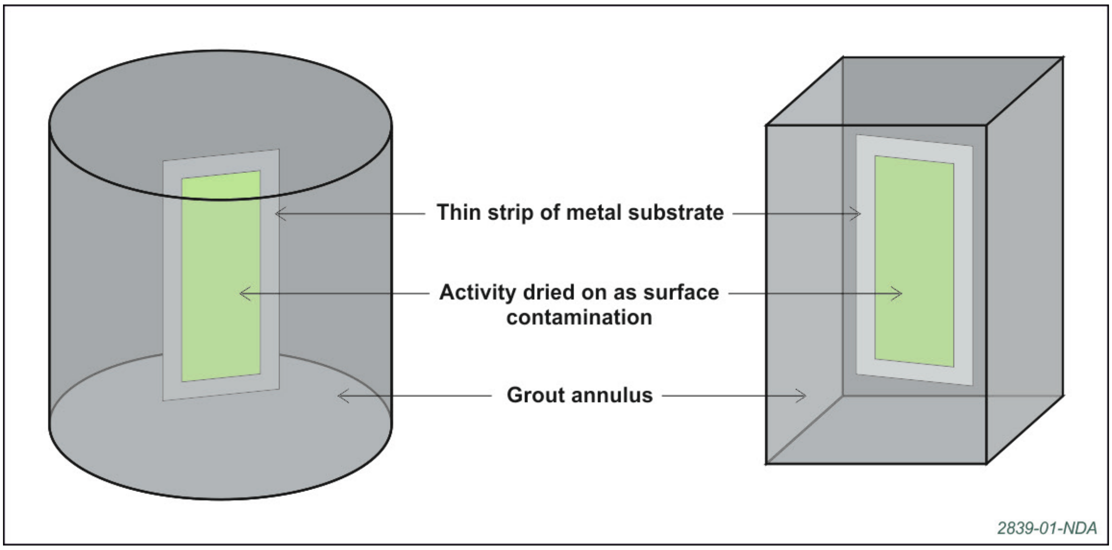


Figure 34: Schematic of dosed homogenous grouted wasteform and dosed Magnox sludge in grout

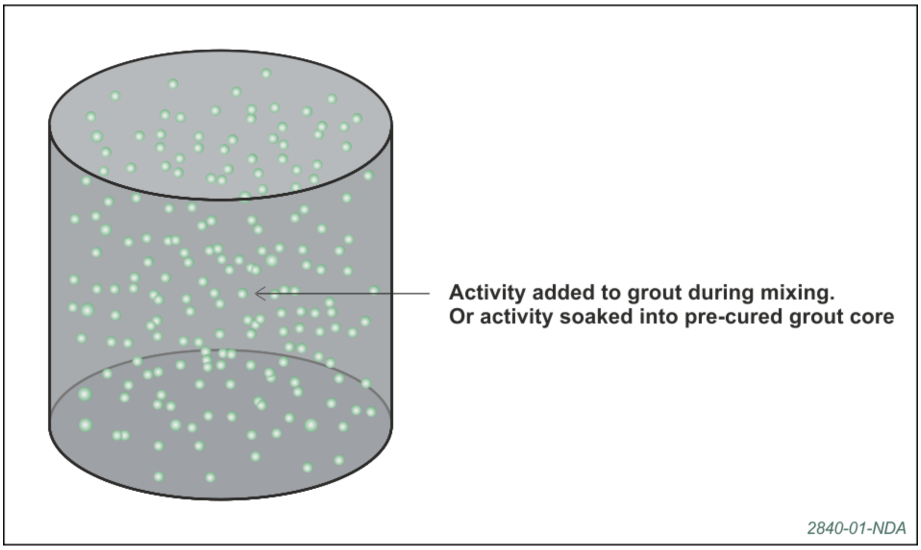


Figure 35: Schematic of unencapsulated dosed Magnox sludge in a boat

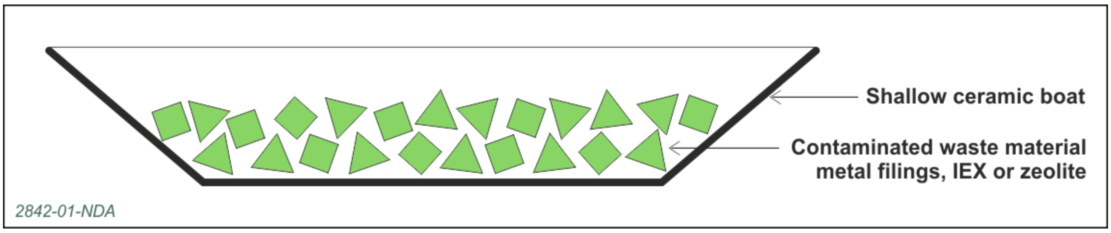
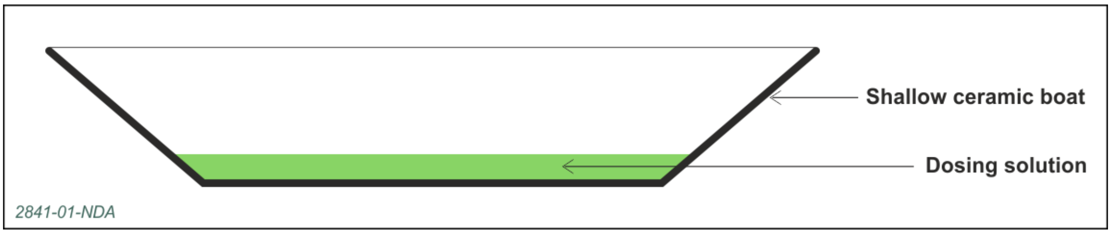


Figure 36: Schematic of Unencapsulated radionuclide solution in a boat



5.3.3 Applying small-scale RF data to all radionuclides

The RF data measured in the limited small-scale tests are used to estimate the RFs for all other radionuclides by grouping all the elements into six groups based on their calculated vapour pressure, for their predicted most likely chemical form, in the assumed case of 1000°C in steam and air. For each volatility group, the elements for which measured RFs exist were first identified. It is then assumed that the highest of these measured RFs applies to all the elements in the volatility group.

As noted above, the RF data measured in the limited number of small-scale tests were used to estimate the RFs for all other radionuclides. This was done by grouping all the elements into six groups based on their volatility [89,90]. The first stage was to determine the most stable chemical form of each element when in equilibrium with steam and air at a temperature of 1000°C, the assumed highest temperature of a fire fault (for example, taking a first principles approach, in these conditions, carbon would combine with oxygen in the air to form carbon dioxide). The volatility of each chemical was then identified, enabling all the elements to be allocated to one of the six volatility groups. Volatility group I has the highest volatility (in fact the chemicals in this volatility group are all gases at 1000°C), while volatility group VI has the lowest volatility. It is assumed that the more volatile a chemical, the greater the RF of the associated radionuclide.

It is not expected that the entire wasteform will reach temperatures near 1000°C, but this assumption provides a starting point for experiments to be carried out for the most pessimistic case. For most tested radionuclides investigated experimentally, at least two temperatures were tested between 150°C and 1000°C. From the scatter observed in the data for particular wasteforms, a judgement was made as to whether a linear interpolation of the RF between any measured values can be supported or whether one conservative RF value should be used to cover the whole temperature range.

The measured RFs from the small-scale active tests (see Section 5.2.2) are used to derive RFs for each generic type of wasteform as a function of temperature. For each volatility group, the elements for which measured RFs exist were first identified. It was then assumed that the highest of these measured RFs would apply to all the elements in that volatility group. For some volatility groups in some wasteforms, no measured RF data were available. In these cases the RFs were conservatively assumed to be the same as those for the next highest (more volatile) group. Since all the chemical forms of the elements in volatility group I are gases in the presence of oxygen, they are always given an RF of 1. It should however be noted that these volatility group I radionuclides can be in different chemical and physical forms (such as C-14 in a graphite block rather than readily mobile as a gaseous form).

The predicted release fractions discussed above are expected to be able to be reduced for specific wasteform types if the associated activity can be quantified in terms of chemical forms that are more stable at elevated temperatures. For example, tritium is assumed to be in a gaseous form and can readily escape from the waste package (for example, in the form of methane gas), but if it is known that the form is more stable, such as tritium within steel, then this can be accounted for in the predicted RF.

The allocations of the elements to the six volatility groups are shown in Table 8. The elements for which some measured RF data are available are underlined.

It is expected that as more volatility data become available then the volatility groups may be revised, or that volatility assignments could be made on an element by element basis. These possibilities are the subject of current research (see [10] tasks 946, 1007 and 1008).

Table 4: Element volatility groups. Radionuclides for which measured RF data exist are highlighted and underlined

Volatility group	Elements
I	Ar, As, At, Br, C, Cl, F, H, He, Hg, I, Kr, N, Ne, O, P, Rn, S, Se, Xe
II	B, Bi, Cd, **Cs**, Fr, Ge, In, K, Li, Na, Os, Po, Rb, Re, Sb, Sn, Tc, Te, Tl
III	Ag, Ba, Be, Ga, Mo, Pb, Ra, **Ru**, W, Zn
IV	Al, Au, Ca, **Co**, Cr, Cu, **Eu**, Fe, La, Mg, Mn, Ni, Pd, **Sr**, **U**, V
V	Ac, **Am**, Bk, Ce, Cf, Cm, Es, Fm, Lr, Md, Nd, No, Np, **Pu**, Rh, Si, Y, Zr
VI	Db, Dy, Er, Gd, Hf, Ho, Ir, Lu, Nb, Pa, Pm, Pr, Pt, Rf, Sc, Sm, Ta, Tb, Th, Ti, Tm, Yb

5.4 Development of validated assessment tools

Validation tests have been performed for the modelling of heat transfer through cementitious grouts, comparing the predicted temperatures as a function of time against those measured in full-scale fire tests. Reasonably good agreement was obtained and it has been concluded that the uncertainty in the heat transfer calculations is small compared to the uncertainty in the experimentally measured radionuclide RF data.

The accuracy with which FE codes can model heat transfer through solid materials such as stainless steel, cast iron and copper is well established. The modelling of heat transfer through cementitious grouts, however, is a specialist application and so we have undertaken work to investigate the accuracy of the methodology. It was realised early on during experimental work that the heat transfer to latent heat of water, and the subsequent progression of a drying front through a cementitious grout would be critical in any modelling of the temperature profile through a heated waste package; the specific heat of a volume of grout being increased by a factor of approximately three (depending on water content) for a temperature range of a few degrees either side of 100°C. As described above, the thermal conductivity and specific heat used in the FE models have been developed from measured data from dried samples by separately adding the effects of the chemical changes and the release of water from the grout and the properties of any encapsulated waste. The density used in the models is also based on measured data. Validation tests have been performed, comparing the predicted temperatures as a function of time against those measured in the full-scale fire tests described in Section 5.2.1. Reasonably good agreement has been obtained and it has been concluded that the uncertainty in the heat transfer calculations is small compared to the uncertainty in the experimentally measured radionuclide RF data (for example, repeated RF measurements for encapsulated floc and sludge wasteforms can vary by a factor of 5).

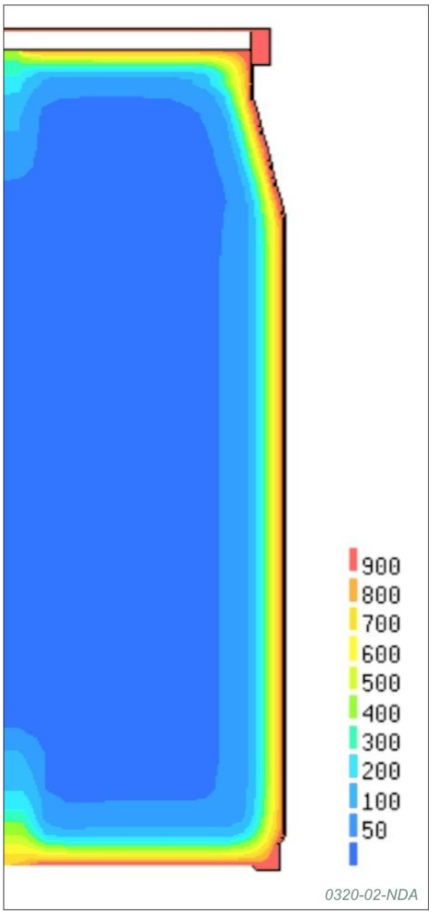
FE models have been produced for a number of different waste packages including:

- the 500 litre drum [91]
- the annular grouted 500 litre drum [92]
- the 3 cubic metre box [93]
- the 3 cubic metre drum [94].

Other waste packages, such as the 2 metre box, 4 metre box and MBGWS box are included for further study in the current research programme. For the 2 and 4 metre boxes, an indication of the temperature experienced when exposed to a fire has been estimated using simple one dimensional models of a section through the side wall, lid or base [95]. From this study, a 4 metre box was assumed to be involved in an all engulfing 1000oC fire of 1-hour duration with a 23-hour cooldown period. The 200mm thick C50 concrete shielding provided a good thermal barrier to heat from the external environment passing through to the inside surface. The predicted peak temperature on the inside surface was 84.9ºC.

Figure 37 shows the predicted temperature profile through a typical 500 litre drum model at the end of a one hour fire at 1000°C. It can be seen that, due to the presence of the cementitious grout, high temperatures are only experienced around the outside surface of the waste package, while the interior of the package remains cool. The heat front advances further at the centre of the base and from the top of the waste container as these are the locations of the two metal bearings for the mixing paddle. Calculations are left to run for periods of up to 48 hours after the cessation of heat input to the package (the point at which the fire has been extinguished). This is in order that all volumes of a package may reach their peak temperature, central regions in particular, often reach peak temperature several hours after heat input to the package has ceased.

Figure 37: FE prediction of the temperature distribution (°C) for a 500 litre drum at the end of a one hour fire [96]



6 Release fractions for standard packages

Two detailed reports are available [97,98] that list recommended waste package RFs for impact events and for fire scenarios respectively. These reports are expected to be superseded as current research delivers updated information in published reports. Due to the timing of the current research programme coinciding with the update of the Disposal System Safety Case the future research outputs from this four-year programme will be presented as an addendum or an update to this status report in due course.

This section discusses the range of impact release fractions encountered and the underpinning test data, modelling or analogy deemed most suitable for representing the RF for a standard package type (see Table 1).

Package RFs are available within the Data Report [9].

6.1 Impact

The RF for a waste package resulting from an impact accident is the mass of particulates of a specified size range released, expressed as a proportion of the mass of the wasteform.

The RF for a waste package resulting from an impact accident is defined as the mass of particulates smaller than a given diameter which cross the waste package boundary, expressed as a fraction of the pre-accident mass of the wasteform (independent of particle size), (see section 3.3.1 for further definition).

Typical values of sub 100 μm impact release fractions for drops from 25 m are in the range 2×10^{-4} to 8×10^{-4} for the majority of package designs that are not specifically intended to be 'robust'. Work is currently underway to provide a new data set for sub 10 μm particle sizes and for the drop heights in the current GDF designs (see [10] tasks 912, 914, 919).

Section 4 describes how the impact performance of waste packages has been demonstrated by physical drop testing.

Depending on the test or analysis data available, the approach to the derivation of impact RFs may differ. In general, measured data from drop tests are used where drop tests form the bulk of the database, but data from FE simulations are used where these better represent the package and impact scenario in question. The recommended values conservatively comprise the highest RF values so far observed in tests or from other analyses. The variability of impact performance means that RFs for either existing or future packages are more likely to be smaller than these values, although they could be higher. The detailed derivations of RFs for most standard packages are described in the impact RF report [97]. In this review the appropriate test or model result is identified and discussed, leading to a predicted RF for that waste package type. Some recent additions to the standard packages (the 500 litre concrete drum, 1 cubic metre concrete drum, RSCs) do not yet have an associated standard RF value and will only have specific RF values for a particular waste stream derived as part of the Disposability Assessment process. Package RF values will be assigned to these new packages as the available data and new finite element modelling results are reviewed. Reference [97] also includes a review of the drop tests and modelling that support our understanding of waste package performance. From drop tests where material is released from the package, the overall RF is conservatively calculated by summing the RF calculated from the particle size distribution of released material and the RF calculated from the particle size distribution of the material collected from de-lidding and skinning.

The approach for assessing impact performance for much of the currently available data set assumes a bounding drop onto an unyielding target. These data will be updated with RFs for drop heights appropriate to the current operational safety case as research progresses (see [10] task 912). Table 1 lists the standard package types and the data used to underpin the currently adopted RFs.

Work is ongoing to improve the quality and consistency of impact accident release fraction data via development of an improved impact methodology and improved FEA models (see [10] tasks 913, 921).

Table 1 describes how current standard package release fractions have been assigned. Note that the newer package types which are now considered 'standard' (concrete drums, RSC) have no associated standard package release fraction yet.

It should be noted that some RFs are defined for 15 m or 25 m drops. This is because either the most appropriate, or the only available, data are from these drop heights. If appropriate for the package under assessment, the RF value can be scaled to the current accident scenario.

6.2 Fire

The RF for a waste package resulting from a fire accident is the weighted sum of released radionuclides, expressed as a proportion of the sum of all radionuclides present within the wasteform, taking account of radiotoxicity and volatility.

The package RF for a waste package resulting from a fire accident is defined as the summation of the amount of radioactive material, per volatility group, that could cross the waste container boundary in the event that a waste package is involved in a fire, expressed as a proportion of the total activity present in the wasteform (see section 3.3.2 for further definition).

This release results from a combination of two components: the heat energy absorbed by the wasteform in the fire and the changes to the wasteform which give rise to mobile activity. All released material in the event of a fire is assumed to be respirable due to the gaseous nature of volatile releases and the small particulate entrained in steam driven releases.

To provide fire release fraction data for use in Disposability Assessments of waste package designs, and for use in safety cases, we have developed a methodology based on FE modelling combined with small-scale active furnace tests (as described in section 5.2.2). For calculating releases from waste packages exposed to fire, we have defined six volatility groups, shown in Table 8 and described further in Section 6.3.3.

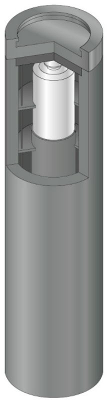
The release fractions of radionuclides in each of the volatility groups, in the event of a fire, are calculated using a post-processor as described in detail in the fire RF report [98].

Typical values of fire release fractions are in the range from 1 for the most volatile radionuclides to 3×10^{-6} for the least volatile for containers not designed specifically to be air tight.

The fire RF report explains the approach for deriving an RF for each of the waste package types. The report starts with a review of the thermal modelling to support the understanding of waste package performance. From the review, the appropriate fire model result is identified and discussed in detail, leading to a predicted RF for that waste package type. Table 1 lists the standard package types and the data used to underpin the currently adopted RFs.

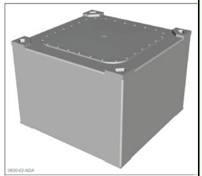
Work is ongoing to improve the quality and consistency of fire accident release fraction data via improved volatility data, improved FEA models and further consideration of the volatility group assignments (see [10] tasks 946, 947, 948, 1007, 1008, 1010, and 1012).

Table 1 Data used to underpin release fractions for standard packages

		Impact accident		Fire accident	
Container	**Schematic**	**Discussion**	**Test, modelling or analogy used to provide RF**	**Discussion**	**Test, modelling or analogy used to provide RF**
Disposal Container		No full-scale testing of disposal containers has been conducted	The impact performance of this waste package type has been modelled [37] and the analyses indicate that although one of the steel/copper outer shell or cast iron structure barriers may be breached in an impact, there will be no loss of containment and therefore no release.	For deriving the fire RF it is assumed that the waste will be placed within a waste container consisting of a thick cast iron structure surrounded by a thick layer of steel or copper. These disposal containers would be completely sealed by welding of the outer steel or copper lid. In a 1000°C fire, the copper outer shell of the disposal container is predicted to reach a relatively uniform temperature of around 870°C. This is well below the melting point of copper (1083°C) and it is therefore concluded that the integrity of the copper of the disposal container will remain intact and that there will be no release of radionuclides from the sealed copper outer	The recommended RF for a disposal container is based on a one dimensional finite element model of a waste container consisting of a copper outer shell with a cast iron structure [99].

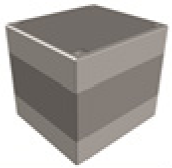
				shell. Similar performance can be expected of a disposal container with a steel outer shell.	
500 litre drum		The 500 litre drum is the most extensively studied waste container with over 50 drop tests having been performed and additional tests and assessments having also been undertaken. FE simulation has also been used to predict the impact performance of 500 litre drums. The chosen data are the highest observed in physical drop tests of a range of drum designs, wasteforms, drop heights, drop orientations and target types.	All RFs come from drop tests of full-scale simulant 500 litre drums onto a flat unyielding target in a base edge or lid edge orientation. In two of the cases the tests were at a lower drop height and the results were linearly scaled to 25 metres (to standardise them) following the standard scaling methodology [100]. All the airborne particulate generated during the tests was measured and included in the RF predictions.	RFs for the 500 litre drum have been derived for the various wastes that can be placed into the drum. These are split into homogenous and heterogeneous wastes. **Homogeneous waste** The fire performance of 500 litre drums containing a homogeneous wasteform has been studied in some detail and we have developed thermal modelling methods based on experimental measurements. Modelling of the 500 litre drum containing homogenous waste has been conducted for a floc encapsulated in a PFA/OPC cementitious grout. Disposability Assessments have considered proposals to adopt the 500 litre drum for immobilising and encapsulating liquor wastes.	**Homogeneous waste** For this waste package type the generic model of a 500 litre drum containing a Magnox sludge immobilised in a cementitious grout has been applied because it has been studied in some detail [59]. To determine the release of radionuclides, the wasteform release versus temperature characteristics for ‘encapsulated floc and sludge wasteforms’ were applied to the wasteform temperatures [96]. **Heterogeneous waste** A finite element thermal calculation representing this particular wasteform has not been performed. Instead the expected thermal performance of this waste package has been based on the results of

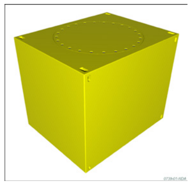
				Heterogeneous waste Several 500 litre drum waste package designs have been approved under the Disposability Assessment process for the encapsulation of heterogeneous (metallic) wastes. These Disposability Assessments were issued in the early 1990s and the assessment of fire performance was based on comparison with full-scale fire tests or by analogy to other waste packages [98]. **Annular grouted 500 litre drum** To obtain the temperature distribution, modelling of the 500 litre annular grouted drum containing compacted waste was been conducted [92].	the homogeneous waste thermal model, described above, modified as necessary to take account of other differences in the waste packages. The main difference between drums of homogeneous wasteform and heterogeneous wasteform is the thermal properties of the wasteform itself. The thermal diffusivity of the homogeneous and heterogeneous wasteforms are very similar, with that of the heterogeneous wasteform being just 4% lower [98]. This similarity justifies the use of the results from the homogeneous thermal model in the assessment of the thermal performance of the heterogeneous wasteform. **Annular grouted 500 litre drum** For this waste package type the RF for a 500 litre drum containing supercompacted pucks of dried Magnox sludge, surrounded by an annulus of BFS/OPC grout is used [98].

3 cubic metre box	 	Four drop tests were carried out by Nirex on the side lifting variant of the 3 cubic metre boxes. In the development programme of the generic 3 cubic metre box, FE modelling of the box was developed and analysed to guide the design process. Particulate was released in three of the four drop tests. Particulate was collected and from both the particulate released from the waste package and that which was loose within the waste packages to create an RF.	The RF recommended is based on a 3 cubic metre box test which was conducted at a drop height of 15 metres. The results were linearly scaled to 25 metres (to standardise them) following the standard scaling methodology [100].	To obtain the temperature distribution, modelling of the 3 cubic metre box containing heterogeneous waste has been conducted for a steel waste encapsulated in a cementitious grout [93]. Several Disposability Assessment submissions have included proposals to adopt the 3 cubic metre box for immobilising and encapsulating heterogeneous wastes.	For this waste package type the generic modelling of the 3 cubic metre box containing heterogeneous waste is used to derive the RF. To determine the release of radionuclides, the wasteform release versus temperature characteristics for 'encapsulated hulls and similar wasteforms' were applied to the wasteform temperatures [98].
3 cubic metre drum		Waste packagers have carried out two drop tests of two 3 cubic metre drum designs [101,102] but no material was released from either drum at a height of 10 metres which is the stack height in the interim storage facilities.	To obtain RF data at 25 metres (if required), the RF for the 3 cubic metre box should be used in the absence of other data [97].	To obtain the temperature distribution, generic modelling of the 3 cubic metre drum containing homogenous waste has been conducted for Magnox sludge encapsulated in a cementitious grout [94]. Both two and three dimensional finite element models were developed so that the effect of the features which were	For this waste package type the model of the 3 cubic metre drum containing homogenous waste has been applied because it has been studied in some detail. To determine the release of radionuclides, the wasteform

				not axi-symmetric (the feet, lifting feature and paddle) could be determined. Nearly 90% of the wasteform was predicted to remain below 100°C, but none of the waste is predicted to remain below 50°C. Its thermal performance is similar to the 500 litre drum containing homogeneous waste, with only the layer of wasteform adjacent to the walls and base of the drum experiencing high temperatures (the top of the wasteform is insulated from the heat of the fire by the capping grout).	release vs. temperature characteristics for 'encapsulated floc and sludge wasteforms' were applied to the wasteform temperatures [98].
MBGWS box		The MBGWS box is in use for the packaging of various ILW items routed though the Miscellaneous Beta Gamma Waste Store. No drop testing or modelling of this waste package has been conducted.	For Disposability Assessment evaluations, impact accident performance was predicted by analogy to other waste package types. The geometry and structure of this waste container is very similar to that of the 3 cubic metre box. It is therefore considered appropriate to adopt the RF from the 3 cubic metre box for this waste package [97].	The MBGWS box is a stainless steel cuboidal container. No modelling of this waste package has been conducted. For Disposability Assessment evaluations, fire accident performance was predicted by analogy to other waste package types.	In order to assess its thermal performance in the event of a fire, a simple one dimensional finite element model has been generated and this predicted that the wasteform would experience peak temperatures of between 250°C and 340°C [103]. To determine the release of radionuclides, the wasteform release versus temperature characteristics for 'encapsulated hulls and similar

					wasteforms' were applied to the wasteform temperatures [98].
2 metre box		Waste packagers are developing designs of the 2 metre box waste package. No drop tests of a 2 metre box waste package have been carried out from a drop height higher than 0.3 metres	The performance has been modelled using simple FE analyses of a 2 metre box waste package from a drop height of 15 metres onto a flat unyielding target [104].	No three dimensional modelling of the 2 metre box waste package has been conducted.	The 2 metre box design is very similar to the 4 metre box (except shorter) in terms of the design of the stainless steel wall and the concrete lining which absorbs most of the heat from a fire. The release fractions calculated for the 4 metre box are considered adequate for application to the 2 metre box [98].
4 metre box		As for the 2 metre box, only 0.3 metre drop tests have been carried out to meet the IAEA Transport Regulations.	FE analyses of the 4 metre box waste package have been carried out using a range of orientations and for a 15 metre drop height [105].	No three dimensional modelling of the 4 metre box waste package has been conducted. For Disposability Assessment evaluations, fire accident performance was predicted by application of modelling of the wall of the 4 metre box to give a good indication of its thermal performance [106]. The model assumed that the self-shielded 4 metre box has a 200 mm thick lining of concrete. The wall was chosen as this region has the shortest heat pathway	To determine the release of radionuclides, the wasteform release versus temperature characteristics for 'encapsulated hulls and similar wasteforms' were applied to the wasteform temperatures [98].

				through to the wasteform.	
6 cubic metre box		Drop tests were carried out in the 1990s on a prototype 6 cubic metre box from various drop heights up to 7 metres and FE analysis was also undertaken in 1996 [107]. The results of these tests and models showed that there was some breakup of the external concrete wall, as well as local cracking. The 6 cubic metre box is undergoing design modifications and physical testing, combined with further FE analysis, at the time of writing.	FE analyses of the original 'WAGR' style 6 cubic metre box in a lid corner drop from 10m onto a flat unyielding target [70].	The 6 cubic metre box is a precast reinforced concrete container which has been approved under the Disposability Assessment process has been used for the packaging of ILW arising from the decommissioning of the Windscale Advanced Gas-Cooled Reactor (WAGR). The Disposability Assessments were issued in the early 1990s and the fire performance was based on analogy to other waste packages [98]. This package is currently being considered for use at other sites and is undergoing design revision for which FE analysis is being conducted.	For this waste package type the model of the 4 metre box wall has been applied because it is of a similar construction. To determine the release of radionuclides, the wasteform release versus temperature characteristics for 'encapsulated hulls and similar wasteforms' were applied to the wasteform temperatures [98].
DV-70 box		A standard RF for this package is yet to be adopted.			

500l concrete drum		A standard RF for this package is yet to be adopted.
1 cubic metre concrete drum		A standard RF for this package is yet to be adopted.
500 litre robust shielded drum		A standard RF for this package is yet to be adopted.
3 cubic metre robust shielded box		A standard RF for this package is yet to be adopted.

7 Concluding remarks

The science and technology underpinning geological disposal of the materials currently considered in the UK radioactive waste inventory is well established. The knowledge base includes information from laboratory studies, full-scale and small-scale testing, computer models and studies from a variety of engineering disciplines that can be used to support the implementation of geological disposal.

The key message emerging from the analysis presented in this status report is that durable waste packages, able to withstand the requirements of transport and GDF operations, and providing sound performance in potential accident conditions, have been produced or can be produced in the future for the wastes considered in the inventory for disposal. Specifically:

1. Experimental data from drop tests of full-size waste packages give us an understanding of the overall performance of packages. This demonstrates for example, that cementitious material within a thin walled package will generally produce an RF in the region of 2×10^{-4} to 8×10^{-4} for the scenarios investigated. Looking at the performance globally also provides such information as the lid-body interface being, for bolted lids, the most likely location for a breach in a container to form.

2. A methodology has been developed which allows the prediction of release fractions for packages which undergo an impact fault. Significant testing programmes of materials, components and software have produced robust inputs to numerical modelling of the dynamic and non-linear processes involved in package impacts allowing reliable predictions of release fractions to be made using benchmarked and validated techniques.

3. Experimental data from full-scale fire testing of inactive simulant waste packages has led to an understanding of the temperature distribution expected within packages. Heating of small scale active and inactive samples has led to empirical measurements of the expected releases of radionuclides of interest from small volumes of waste.

4. A methodology has been developed which allows the prediction of release fractions from packages exposed to a fire. This stems from thermodynamic calculations of volatility of the most likely chemical form for particular radionuclides of interest. For differing wasteforms, measurements have been made, often at a variety of temperatures, which allow volatilities to be assigned to six groupings of radionuclides with similar volatility, at different temperature ranges. Together with materials models such as one describing the complex thermal characteristics of grouts, numerical modelling has been used to calculate the temperatures experienced by small volumes of waste packages. From a combination of the expected temperatures and volatilities, an estimate of the total release of radionuclides from the package can be made.

Information contained in the suite of research status reports has been used to underpin the development of the 2016 gDSSC. In particular, information from this status report has been used to provide technical underpinning to the expected performance of waste packages should these be involved in an accident during transport or GDF operations.

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