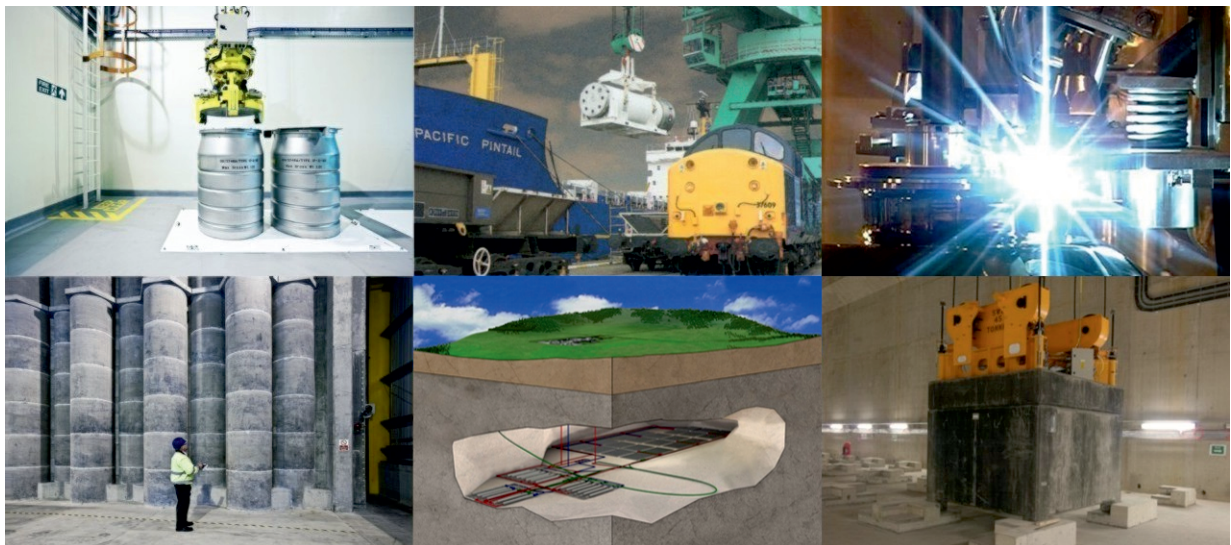


Geological Disposal

Guidance on the application of the Waste Package Specifications for unshielded waste packages

August 2014



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**WASTE PACKAGE SPECIFICATION AND GUIDANCE DOCUMENTATION
GUIDANCE ON THE APPLICATION OF THE WASTE PACKAGE SPECIFICATIONS
FOR UNSHIELDED WASTE PACKAGES**

Executive Summary

This document forms part of the Waste Package Specification and Guidance Documentation (WPSGD), a suite of documents prepared and issued by Radioactive Waste Management Ltd (RWM). The WPSGD is intended to provide a 'user-level' interpretation of the RWM packaging specifications, and other aspects of geological disposal, to assist UK waste packagers in the development of plans for the packaging of higher activity waste in a manner suitable for geological disposal.

Key documents in the WPSGD are the *Waste Package Specifications* (WPS) which define the requirements for the transport and geological disposal of waste packages manufactured using standardised designs of waste container. The WPS are based on the high level requirements for all waste packages as defined by the *Generic Waste Package Specification* (GWPS) and are derived from the bounding requirements for waste packages containing a specific category of waste, as defined by the relevant *Generic Specification*.

This document provides guidance to support the WPS that have been produced for the 'unshielded waste packages' which are identified by the generic Disposal System Technical Specification as suitable for the packaging of low heat generating waste for geological disposal. It provides an explanation of the rationale behind the definition of the requirements together with information to assist waste packagers in the development of approaches for the packaging of waste in a manner that will allow those requirements to be achieved.

The WPSGD is subject to periodic enhancement and revision. Users are therefore advised to refer to <http://www.nda.gov.uk/RWM/producers/detail.cfm#specifications> to confirm that they are in possession of the latest version of any documentation used.

WPSGD DOCUMENT NUMBER WPS/701- VERSION HISTORY		
VERSION	DATE	COMMENTS
WPS/701/01	September 2014	Aligns with Generic Specification for waste packages containing low heat generating waste (NDA/RWMD/068) as published August 2012 Replaces WPS/700, WPS/710, WPS/715 and WPS/720.

List of Contents

Executive Summary	iii
1 Introduction	1
2 Background	3
2.1 The definition and purpose of packaging specifications	3
2.2 The role of the waste package in geological disposal	4
2.3 The definition of waste package types	5
3 Unshielded waste packages	7
3.1 Standardised designs of waste container for the manufacture of unshielded waste packages	7
3.2 The transport of unshielded waste packages	10
3.3 The disposal of unshielded waste packages	12
4 Packaging requirements for unshielded waste packages	13
4.1 Requirements for waste containers	14
4.2 Requirements for wasteforms	29
4.3 Requirements for waste packages	30
5 Summary	61
References	62
Appendix A Constraints placed on Type B transport packages by the IAEA Transport Regulations	67
Glossary of terms used in this document	68

Abbreviations and acronyms used in this document

ACT	accident conditions of transport
ALARA	as low as reasonably achievable
ALARP	as low as reasonably practicable
BSL	Basic Safety Level
BSO	Basic Safety Objective
DBA	design basis accident
DSS	Disposal System Specification
DSSC	Disposal System Safety Case
DSTS	Disposal System Technical Specification
EBS	engineered barrier system
ESC	Environmental Safety Case
GDF	geological disposal facility
GDFD	Generic Disposal Facility Designs
GTSD	Generic Transport System Designs
GWPS	Generic Waste Package Specification
HEU	highly enriched uranium
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
ILW	intermediate level waste
LEU	low enriched uranium
LHGW	low heat generating waste
LLW	low level waste
LoC	Letter of Compliance
LSL	lower screening level
MBGWS	Miscellaneous Beta Gamma Waste Store
MNOP	maximum normal operating pressure
NCT	normal conditions of transport
NDA	Nuclear Decommissioning Authority
ONR	Office for Nuclear Regulation
RWM	Radioactive Waste Management Limited
SAPs	Safety Assessment Principles
SWTC	standard waste transport container
USL	upper screening level
WAC	waste acceptance criteria
WPS	Waste Package Specification

1 Introduction

The Nuclear Decommissioning Authority (NDA), through Radioactive Waste Management Ltd (RWM), is responsible for implementing UK Government policy for long-term management of higher activity radioactive wastes, as set out in the *Implementing Geological Disposal* White Paper [1]. The White Paper outlines a framework for managing higher activity radioactive waste in the long term through geological disposal, which will be implemented alongside the ongoing interim storage of waste packages and supporting research.

RWM produces packaging specifications as a means of providing a baseline against which the suitability of plans to package higher activity waste for geological disposal can be assessed. In this way RWM assists the holders of radioactive waste in the development and implementation of such plans, by defining the requirements for waste packages which would be compatible with the anticipated needs for transport to and disposal in a geological disposal facility (GDF).

The packaging specifications form a hierarchy which comprises three levels:

- The *Generic Waste Package Specification* (GWPS) [2]; which defines the requirements for all waste packages which are destined for geological disposal;
- *Generic Specifications*; which apply the high-level packaging requirements defined by the GWPS to waste packages containing a specific type of waste; and
- *Waste Package Specifications* (WPS); which apply the general requirements defined by a Generic Specification to waste packages manufactured using standardised designs of waste container.

For waste packages containing low heat generating waste¹ (LHGW), RWM has produced the *Generic specification for waste packages containing low heat generating waste* [3].

As a means of making the full range of RWM packaging specifications available to waste producers and other stakeholders, a suite of documentation known as the *Waste Package Specification and Guidance Documentation* (WPSGD) is published and maintained for ready access (via <http://www.nda.gov.uk/RWM/producers/detail.cfm#specifications>).

The WPSGD includes the WPS for the waste packages that produced from the standardised designs of waste container that are identified by the generic Disposal System Technical Specification (DSTS) [4], together with explanatory material and guidance that users will find helpful in the development of proposals to package waste.

For further information on the extent and the role of the WPSGD, reference should be made to the *Introduction to the RWM Waste Package Specification and Guidance Documentation* [5].

The DSTS identifies a number of standardised designs of waste container that have been shown to be suitable for the packaging of such wastes for transport to and disposal in a GDF, including five² which can be used to produce 'unshielded waste packages'. This document provides guidance on the application of the requirements specified by the WPS to proposals to package waste using those waste container designs. Users are directed to guidance on the achievement of the required properties of wasteforms [6, 7] which should be considered alongside this document when they are developing plans for the packaging of waste.

¹ This broad category of waste includes intermediate level waste (ILW), and other wastes with similar radiological properties.

² The 500 litre drum, two variants of the 3 cubic metre box, the 3 cubic metre drum and the MBGWS box.

The remainder of this document is structured in the following manner:

- Section 2 provides background information on the manner in which RWM defines the requirements for waste packages, and the role that packaging specifications play in assessing the suitability of proposed waste packages for geological disposal.
- Section 3 provides a brief summary of the properties of unshielded waste packages and the manner in which they are handled during transport to and disposal in a GDF.
- Section 4 explains the manner in which the requirements of the Generic Specification for waste packages containing LHGW are applied to unshielded waste packages. This is achieved by:
 - (i) explaining the rationale behind the definition of the requirements in the Generic Specification;
 - (ii) summarising how those requirements are applied to the unshielded waste packages that could be manufactured using the existing standardised designs of waste container; and
 - (iii) providing guidance as to how those requirements can be achieved.

2 Background

2.1 The definition and purpose of packaging specifications

When radioactive waste is disposed of in an operational GDF it must be compliant with the waste acceptance criteria (WAC) defined for that facility. WAC would be expected to be produced by the facility operator, overseen by the relevant regulatory authorities, and would be based on the safety cases produced for the operational and post-closure periods of the facility.

In the UK, plans for the geological disposal of higher activity radioactive waste are still at an early stage, so the information necessary to develop WAC is not available. However, in order that wastes can be converted into passively safe and disposable forms, as soon as is reasonably practicable, RWM produces packaging specifications. These specifications define the standard features and performance requirements for waste packages which will be compatible with the anticipated systems and safety cases for transport to and disposal in a GDF. In this way they play an important part in the assessing the suitability of waste packages for geological disposal and may thus be considered as the *preliminary* WAC for a future GDF.

RWM has established the *Disposability Assessment Process* [8] to support those responsible for the packaging of higher activity wastes by demonstrating that the waste packages they propose to produce will be passively safe and disposable, and in line with regulatory expectations for the long term management of the waste [9]. In this manner RWM also demonstrates that waste packages will be capable of providing the barrier to the release of radionuclides and other hazardous materials that is required of them as part of a multiple barrier geological disposal system. A *Letter of Compliance* (LoC) is issued for each specific design of waste package which has been shown to be disposable by way of the Disposability Assessment Process.

The Disposability Assessment Process also plays an important role in underpinning the generic Disposal System Safety Case (DSSC) [10] by demonstrating that the geological disposal concepts considered therein will be appropriate for the actual wastes they will be expected to cover. The process also serves to identify wastes that could challenge the disposal concepts currently assumed for particular categories of waste and thereby allow early consideration of what changes may be required to these concepts to permit such wastes to be accommodated. RWM has produced guidance on the manner by which waste packagers should prepare submissions for the disposability assessment of their proposals to package waste [11].

With waste packages being manufactured at many sites throughout the UK, and by a number of different organisations, the needs of ensuring cost-effectiveness, safety and environmental protection in the long-term are promoted by the adoption of common approaches to waste packaging. In support of these needs, RWM has defined a range of waste containers with standardised features (e.g. dimensions, handling/stacking arrangements) which can be used to produce waste packages. The definition of waste containers in this way will help to ensure a high level of confidence that all waste packages manufactured according to the requirements set out in the WPSGD will be compatible with future transport and GDF infrastructure and facilities.

RWM considers that the existing range of standardised waste container will be suitable for use in the packaging of the majority of the ILW³ predicted to arise in the UK. However, RWM acknowledges that these waste containers may not suit all of the needs of

³ These containers may also be suitable for use in the packaging of a wider range of LHGW, as discussed in the Generic Specification [3].

individual waste producers, and that additional designs may be required for the packaging of particular wastes. RWM uses the Disposability Assessment Process to consider the suitability of alternative designs of waste container to produce disposable waste packages, by way of a demonstration of compliance of the proposed design with the relevant Generic Specification. If such compliance can be shown, RWM can then use the concept change control management process to ensure that the waste packages that would result from the use of the new container design would be compatible with all aspects of RWM's plans for disposal concept. If this can be shown to be the case, the container will be added to those identified by the DSTS, and a WPS produced for the waste packages it could be used to manufacture.

2.2 The role of the waste package in geological disposal

The waste package provides the most immediate barrier to the release of radionuclides and other hazardous materials from the waste it contains during interim storage, transport and when it forms part of a multiple barrier geological disposal system. It can also play a role in protecting individuals from the radiation emitted by the radionuclides it contains during interim storage, transport and the GDF operational period.

The barrier provided by a waste package can be considered to comprise two components, each of which can act as a barrier in its own right:

- The waste container, which provides a physical barrier and also enables the waste to be handled safely during and following waste package manufacture. Containers can be manufactured from a range of materials with designs selected to suit the requirements for the packaging, transport and disposal of the wastes they contain.
- The wastefrom, which can be designed to provide a significant degree of physical and/or chemical containment of the radionuclides and other hazardous materials associated with the waste. The wastefrom may comprise waste which has been 'immobilised' (e.g. by the use of an encapsulating medium such as cement) or that which may have received more limited pre-treatment prior to packaging (e.g. size reduction and/or drying).

It is the performance of the barrier(s) provided by the waste package that packaging specifications seek to address, as well as defining requirements for waste packages which take into account the other needs of the long-term management of waste packages, notably their transport.

In the generic DSTS [4] the concept of *safety functions* is developed as a means of defining the roles played by each of the barriers in the post-closure performance of a GDF. This concept is further developed in the DSSC in which the safety functions that are required of waste packages during transport and the GDF operational period are also considered [12]. The GWPS identifies the safety functions specific to waste packages which will be required during transport and the period up to the time when a GDF is backfilled, and during the GDF post-closure period. The safety functions required in these periods can be summarised as:

- During transport and the GDF operational period:
 - Provide containment of radionuclides and other hazardous materials during normal operations and under accident conditions;
 - Limit radiation dose⁴ to workers and members of the public;
 - Preclude criticality;
 - Provide the means of safe handling; and

⁴ In this context radiation dose is that which could result from exposure to direct radiation from the surface of the waste package.

- Withstand internal and external loads.
- During the GDF post-closure period:
 - Provide containment of radionuclides and other hazardous materials;
 - Contribute to the overall performance of the engineered barrier system (EBS);
 - Contribute to ensuring that, following GDF closure, a criticality event is not a significant concern; and
 - Withstand internal and external loads.

Both the waste container and the wasteform can contribute to the achievement of the required performance of the waste packages, the relative importance of each generally depending on the robustness of the former. This is illustrated in Figure 1 which shows in stylised form how the use of a more robust waste container can reduce the required contribution of the wasteform to overall waste package performance.

Figure 1 Relative contribution of the waste container and the wasteform to waste package performance

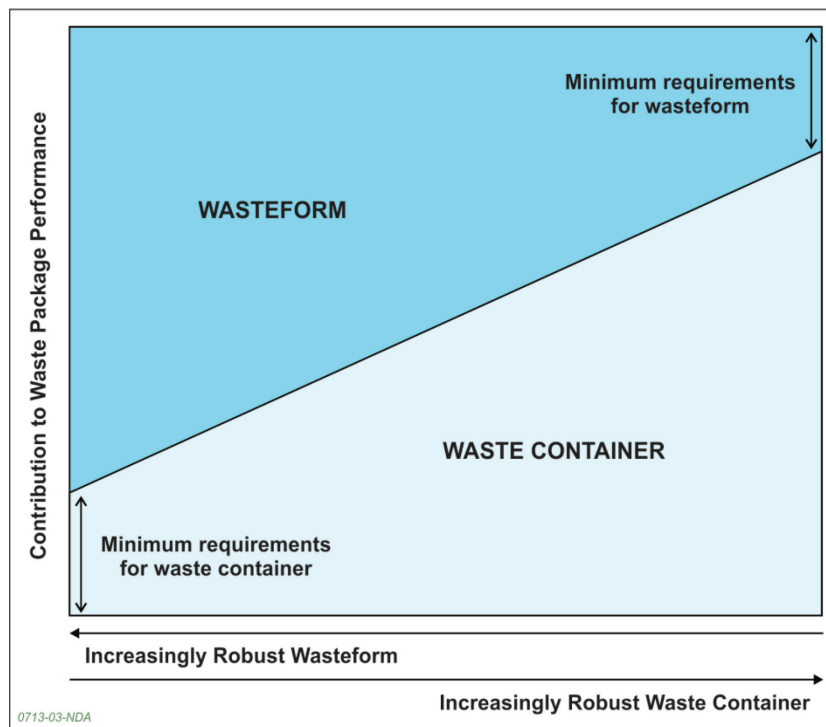


Figure 1 also shows that for all waste packages both the waste container and the wasteform will be required to play some role. It should also be noted that it is the overall performance of the waste package, rather than that of its two components, that is the governing factor in judging its disposability.

2.3 The definition of waste package types

A variety of waste container designs have been proposed for the packaging of LHGW for geological disposal. These designs can be grouped into three basic types, on the basis of the general nature of the waste packages they are used to produce:

- For use with wastes with low specific activity, such as would not generally require the extensive use of remote handling techniques, waste containers

incorporating integral radiation shielding⁵ can be used to create *shielded waste packages*. Such waste packages would generally be expected to be capable of being transported through the public domain without additional protection and would therefore qualify as transport packages in their own right.

- For higher activity LHGW, such as would generally require the use of remote handling techniques, relatively thin-walled (i.e. a few mm) metal containers can be used to create *unshielded waste packages*. Because of their high external radiation dose rate, or requirements for the containment of their contents, such waste packages would be expected to be transported through the public domain in reusable shielded transport containers.
- For all types of LHGW, thick-walled (i.e. many 10's of mm thick) waste containers can be used to provide both radiation shielding and physical containment of their contents, and to create *robust shielded waste packages*. Such waste packages are capable of being stored, transported and disposed of without the need for remote handling techniques or for additional shielding or containment.

⁵ If needed, to ensure that external radiation dose rates do not exceed the regulatory limits for transport.

3 Unshielded waste packages

As stated above, the main distinguishing feature of an unshielded waste package is that no explicit aspect of its design is aimed at reducing the external radiation due to its radionuclide contents. Traditionally the waste containers used for the manufacture of unshielded waste packages have been made from stainless steel with thicknesses of the order of a few mm. Such a material will completely shield radiation from alpha-emitting radionuclides, cause a significant reduction in beta radiation, but will have little or no shielding effect on gamma, neutron or X-radiation. A major consequence of the use of such a container for the packaging of waste is that, to ensure that the radiation exposure of workers and members of the public is minimised, additional shielding of the waste packages will be required during their transport (Section 3.2) and that, following their receipt at a GDF, they will be remotely handled (Section 3.3).

The DSTS [4] identifies five standardised designs of waste container that can be used for the manufacture of unshielded waste packages, and for which WPS have been produced. Each WPS defines a number of standard features with which all waste containers of that type must comply. These comprise:

- a dimensional envelope;
- standardised lifting, tie-down and/or stacking features;
- an identifier format and locations; and
- a requirement for the durability of integrity.

Also included are a number of required waste package properties, namely:

- a maximum gross mass; and
- a stacking requirement.

Finally the WPS includes a number of waste package performance requirements for:

- wasteform properties;
- radionuclide inventory related properties:
 - external dose rate;
 - heat output; and
 - criticality safety.
- surface contamination;
- gas generation; and
- impact and fire accident performance.

3.1 Standardised designs of waste container for the manufacture of unshielded waste packages

Five standardised designs of waste container⁶ are identified by the DSTS as being suitable for use in the packaging of LHGW to form unshielded waste packages. The following sub-sections describe the basic features of each.

⁶ This includes the Miscellaneous Beta Gamma Waste Store (MBGWS) Box which has not yet been shown to be suitable for the manufacture of disposable waste packages.

3.1.1 500 litre drum

The 500 litre drum [13] (Figure 2) is used for the packaging of operational and legacy wastes with a wide range of physical, chemical and radiological properties. Within the standard dimensional envelope defined for the 500 litre drum waste container a number of variants have been developed to accommodate the process requirements for the conditioning of several different types of waste. This has resulted in the production of a number of different wastefrom types including:

- heterogeneous wastefroms - solid wastes in-filled with a fluid grout;
- homogenous wastefroms - liquid, sludge and slurry wastes, in-drum mixed with grout; and
- annular grouted wastefroms - 'pucks' of compacted soft waste, surrounded by a grout annulus.

Figure 2 The 500 litre drum waste container

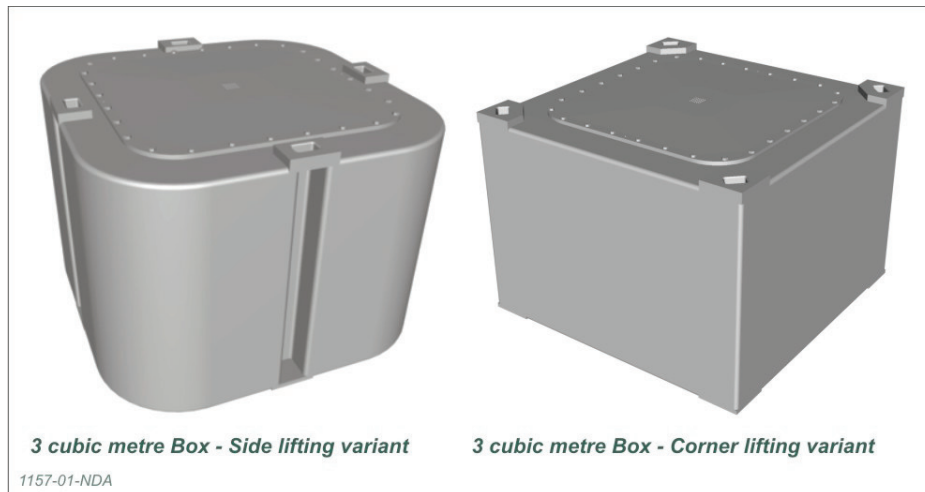


To permit the safe and efficient handling and stacking of 500 litre drum waste packages during their long-term management (including transport and disposal) it is anticipated that 'stillages' will be used, each containing a 2x2 array of waste packages (Figure 2).

3.1.2 3 cubic metre box

The 3 cubic metre box (Figure 3) is a large cuboidal waste container typically used for the conditioning of solid legacy wastes.

Within the standard dimensional envelope defined for the 3 cubic metre box two distinct variants have been developed to accommodate the process requirements for packaging particular waste types at different sites [14, 15]. The two variants are mainly distinguished by their lifting features, which are located at the mid points of the sides of the container (the 'side-lifting' variant) or at the corners of the container (the 'corner-lifting' variant).

Figure 3 Variants of the 3 cubic metre box waste container**3.1.3 3 cubic metre drum**

The 3 cubic metre drum [16] (Figure 4) is a cylindrical waste container which is generally used for the packaging of liquid, sludge and slurry wastes which are typically conditioned of by a process of 'in-drum mixing' of the waste with an immobilising material.

Figure 4 3 cubic metre drum waste container**3.1.4 Miscellaneous Beta Gamma Waste Store box**

The Miscellaneous Beta Gamma Waste Store (MBGWS) box [17] (Figure 5) is a cuboidal waste container which is currently used for the storage of a range of unencapsulated solid ILW at Sellafield. It is anticipated that, prior to export to a GDF the waste currently held in MBGWS boxes, which have been fabricated from either mild or stainless steel, will be further conditioned to produce disposable waste packages.

Figure 5 **Miscellaneous Beta Gamma Waste Store box**



3.2 The transport of unshielded waste packages

The transport of radioactive materials is subject to a number of requirements, as implemented into UK law⁷, notably the IAEA *Regulations for the Safe Transport of Radioactive Material*⁸ [18]. The IAEA Transport Regulations define general requirements and, in some cases, quantified limits for a range of properties of radioactive materials which apply to their transport and these are, where relevant, incorporated into the packaging specifications.

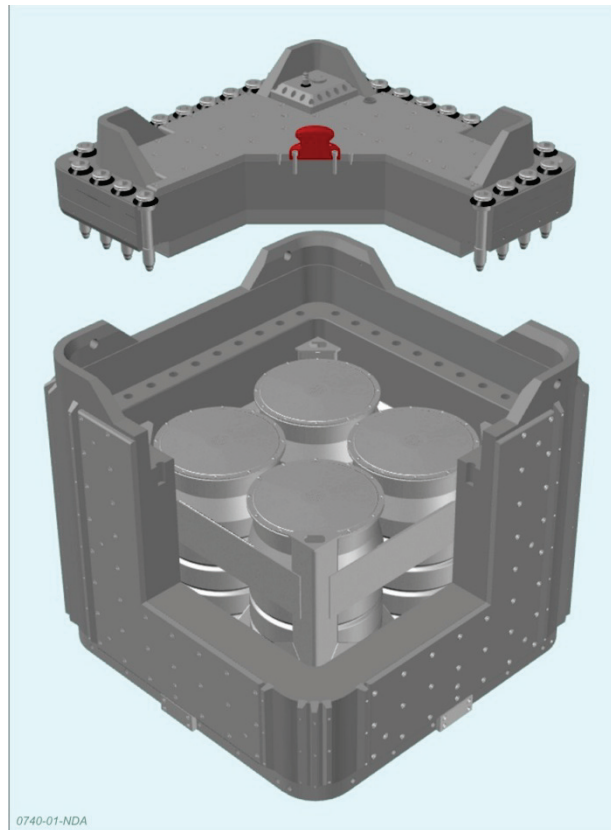
The distinction between a ‘waste package’ and a ‘transport package’ is important here as it influences the manner by which the requirements of the IAEA Transport Regulations are applied to waste packages. A waste package will, in general, comprise a container in which conditioned waste is placed and which is suitable for disposal without further treatment. A transport package is an item suitable for transport and which may comprise of one or more waste packages contained within a protective transport container.

The IAEA Transport Regulations define two categories of transport package which are suitable for the transport of LHW; Type B and Type IP. It is currently assumed that all of the existing designs of unshielded waste package will be transported using one of a range of shielded transport containers (the ‘standard waste transport container’ - SWTC - Figure 6) as part of a Type B transport package. This permits them to be used for the packaging of wastes with relatively high specific activities, including those containing significant quantities of fissile material.

⁷ The Radioactive Materials Transport Team of the ONR has regulatory responsibility for the transportation of radioactive material in Great Britain.

⁸ This reference will be referred to as the ‘IAEA Transport Regulations’ in the remainder of document, and direct reference made to relevant Paragraphs in those Regulations.

Figure 6 Unshielded waste packages in a SWTC



Two regimes under which transport packages can be carried, these being under the conditions of 'exclusive use' or 'non-exclusive use'. Paragraph 221 defines 'exclusive use' as:

'the sole use, by a single consignor, of a conveyance or of a large freight container, in respect of which all initial, intermediate and final loading and unloading is carried out in accordance with the directions of the consignor or consignee'.

If all of these provisions do not apply to a transport operation it is deemed to take place under the conditions of 'non-exclusive use' which are less onerous in terms of the operational controls placed on transport, but which place more onerous limits on some transport package properties, such as external radiation dose rates.

Appendix A summarises the constraints that the IAEA Transport Regulations place on the contents and properties of Type B transport packages.

In the Generic Specification which applies to waste packages containing LHGW (i.e. [3]) it is assumed that the properties of transport packages would qualify them for transport under the conditions of non-exclusive use and therefore the more onerous limits are applied. However this does not preclude transport under the conditions of exclusive use so that benefit can be gained from the less onerous limits, provided that this would result in a 'lifetime dose'⁹ from the waste which can be shown to be as low as reasonably achievable (ALARA).

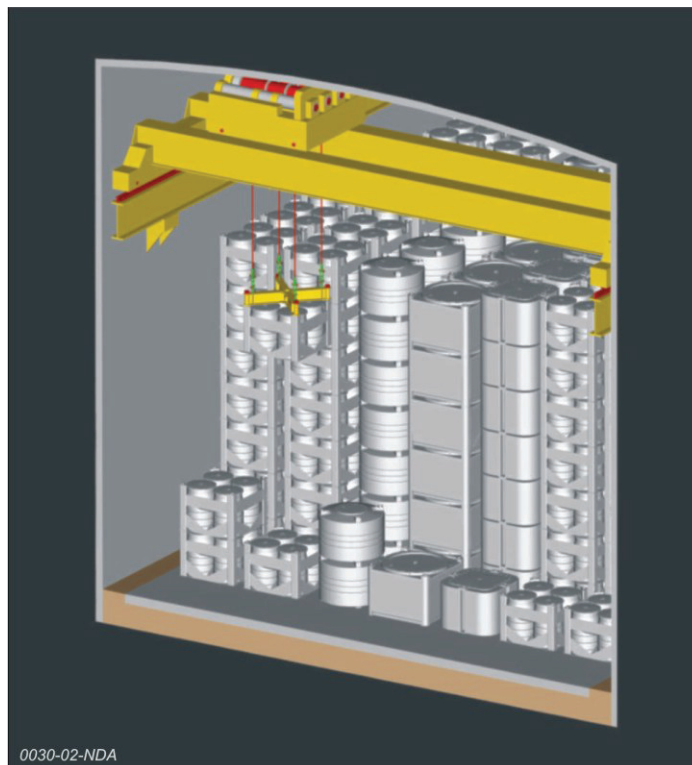
⁹ The lifetime dose includes all doses to workers and members of the public that would result from the retrieval, packaging, interim storage, transport and disposal of the waste.

3.3 The disposal of unshielded waste packages

Following receipt at the GDF, SWTCs containing unshielded waste packages will be transferred (usually from a rail vehicle, although road transport may be used in some cases) on to a transporter for transfer underground. Once underground the SWTC will be removed from the transporter and transferred to an inlet cell where the lid will be removed and the waste package(s) removed. The waste package(s) will then be transferred to the disposal vaults by means of an automated system and emplaced in the vaults in stacks (up to seven-high depending on the waste package design and the geological environment in which the GDF is constructed) using an overhead crane, as shown in Figure 7.

At some point in the future, the disposal vaults will be closed, prior to which, depending on the geological environment in which the GDF is constructed, they may be backfilled as a means of filling voids and, in some cases, providing additional chemical conditioning of the waste. The period during which emplacement of waste packages occurs, together with the time until the vault is permanently closed, is generally referred to as the 'operational period'. Following the end of this period, the GDF will enter the 'post-closure period'.

Figure 7 Cross-section through disposal vault for unshielded waste packages in higher strength rock environment



4 Packaging requirements for unshielded waste packages

This Section defines the requirements for unshielded waste packages which are derived directly from the high-level requirements for all waste packages containing LHGW which are defined by the Generic Specification for such wastes (i.e. [3]).

The format of this section is to:

- identify the generic packaging requirements for all waste packages (shown in ***bold italic*** type) as defined by the GWPS, together with those defined for waste packages containing LHGW (shown in **bold** type) by the Generic Specification; as they apply to all potential designs of unshielded waste package;
- explain the basis for the definition of those requirements;
- describe how those requirements are applied to unshielded waste packages manufactured using each of the existing standardised designs of waste container; and
- discuss the factors that influence their means of achievement.

In general the packaging requirements discussed below apply to the waste package as a whole, but in practice the manner in which they are achieved will depend on a number of factors including the nature of the waste container, the physical, chemical and radiological properties of the waste and the means by which the waste is conditioned for disposal. Accordingly, to aid the application of the packaging requirements in the development of plans to package waste, they are grouped in a manner to reflect those which are most directly related to the waste container, the waste form, and the waste package as a whole.

It should be noted that, where the words 'shall' and 'should' are used in the definition of packaging requirements, their use is consistent with the recommendations of BS7373:1998 [19] in that they have the following meaning:

- 'shall' denotes a limit which is derived from consideration of a regulatory requirement and/or from a fundamental assumption regarding the current designs of the transport or disposal facility systems;
- 'should' denotes a target from which relaxations may be possible if they can be shown¹⁰ not to result in any significant reduction in the overall safety of the geological disposal system.

A number of the packaging requirements (e.g. heat output, gas generation and criticality safety) include quantified 'screening levels'. These values are defined to provide guidance to waste package designers by indicating the levels below which no specific justification of waste package performance would be required as part of a submission for the disposability assessment of a packaging proposal. It should be noted that these screening levels are not intended to be used as a sole basis for the development of packaging proposals as, in many cases, the actual limiting values for specific designs of waste package may be significantly higher.

¹⁰ This would generally be by way of the Disposability Assessment Process.

4.1 Requirements for waste containers

The properties of the waste container shall be such that, in conjunction with those of the wasteform, it satisfies all of the requirements for the waste package.

In Section 2.2, the contribution that the waste container can make to the overall properties and performance of a waste package was discussed. For some of the required waste package properties (e.g. external dimensions, lifting features, and identification) the waste container will generally satisfy the requirement, whereas for others (e.g. stackability, accident performance) it may only play a partial role, the actual extent of the role played by the waste container depending on its robustness, as illustrated by Figure 1.

In general terms it is expected that the waste containers for the existing designs of unshielded waste package will provide the waste package with adequate:

- mechanical strength to:
 - withstand stacking forces (Section 4.1.3);
 - resist damage due to pressurisation by internally generated gases (Section 4.3.6);
 - ensure that the specified impact accident performance (Section 4.3.8) can be achieved; and
 - withstand other loads that may occur during the long-term management of the waste package, as required by the generic Environmental Safety Case (ESC) [20].
- thermal properties to ensure that the required fire accident performance (Section 4.3.8) and other requirements for the thermal performance of the waste package will be achieved; and
- resistance to degradation to ensure the overall integrity of the waste container is maintained for an adequate period (Section 4.1.5).

The standard features of the existing standardised designs of unshielded waste container are shown in Figures 8 to 11.

Figure 8 Standard features of the 500 litre drum

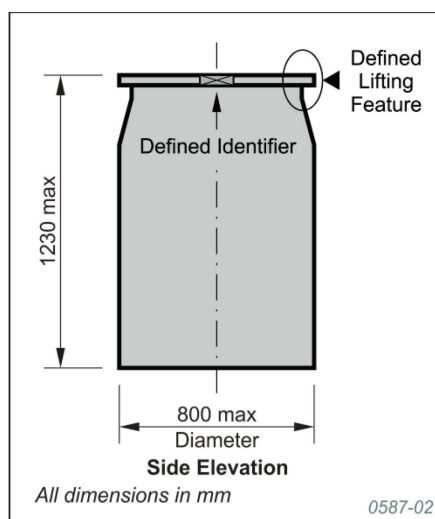


Figure 9 Standard features of the 3 cubic metre boxes

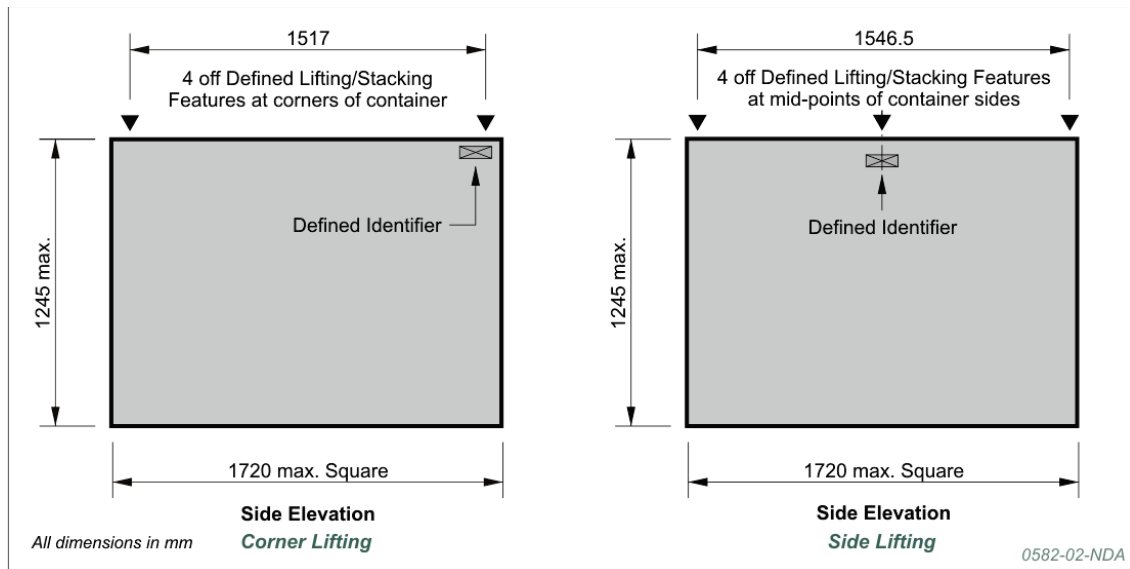


Figure 10 Standard features of the 3 cubic metre drum

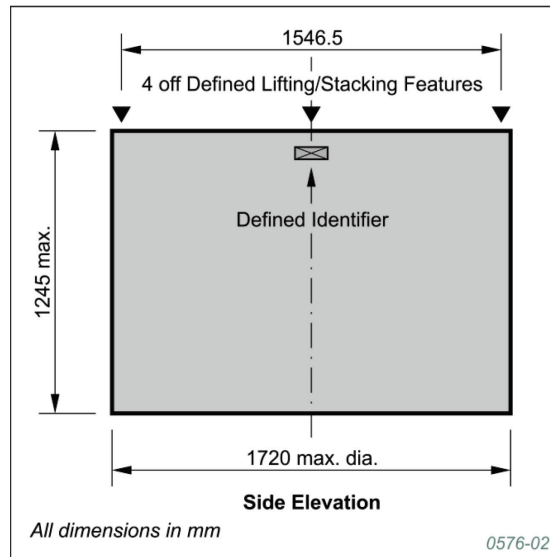
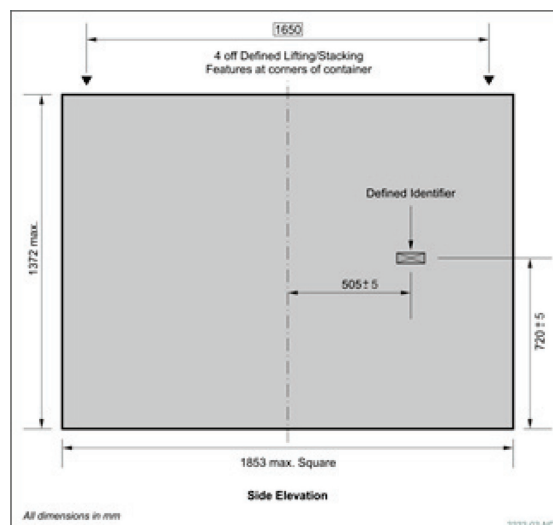


Figure 11 Standard features of the MBGWS box



The fabrication of a waste container with the required dimensions, shape and containment properties will place a number of demands on the properties of the materials used. For example fabrication might involve forming (i.e. bending, spinning etc.), joining (i.e. welding etc.) and machining (i.e. tapping and threading of bolt holes etc.).

The dimensions and shape of a waste container must also be maintained within a defined envelope during and following waste package manufacture. It is therefore important that material properties such as yield strength, creep resistance and shrinkage are suitable to ensure the long-term dimensional stability of waste packages. Degradation of the wasteform, particularly as a result of the corrosion of 'reactive' metals such as uranium, can lead to wasteform expansion and the waste container should be sufficiently rigid to allow it to resist this and ensure that the waste package dimensions remain within the defined envelope.

Austenitic stainless steel, typically Type 316L, has been extensively used for the manufacture of containers for unshielded waste packages. The choice of this material is largely historic, and is supported by a number of properties it offers including:

- Extremely low general corrosion rates [21]: in atmospheric and controlled stored environments, as well as to typical wastes and conditioning materials. This results in a reduced need for a 'corrosion allowance' in the design of waste containers, thus reducing cost and waste container mass.
- It is strong, yet ductile and so is readily cut, formed and machined, especially when used in relatively thin sections, as permitted by its corrosion resistance.
- It can be welded by standard methods without a need for extensive pre- or post-weld heat treatment. As a consequence suitably experienced commercial fabrication shops are readily available.
- Common grades of stainless steel are widely used in other industries and so they are readily available in a range of product forms.
- It has a good long-term track record in analogous industrial applications.

Other stainless steels (notably Type 304L) have also been used in the fabrication of waste containers but this has tended to be restricted to thicker sections, such as lifting features and lid flanges. Duplex stainless steels have also been identified as being suitable for the fabrication of waste containers as they offer higher strength and corrosion resistance, and hence can be used with lesser thicknesses than austenitics. Duplex steels are however potentially more difficult to form and weld and may not be suitable in all cases.

One variant of the MBGWS box has been fabricated from mild steel, a material that does not possess the same corrosion resistant properties of stainless steel. The disposability of waste packages made from such waste containers has not yet been formally assessed but it is questionable as to whether they could be shown to possess adequate long-term durability (see Section 4.1.5).

4.1.1 External dimensions

The external dimensions of the waste package shall be compatible with the transport and GDF handling systems.

The overall dimensions of a transport package should not exceed 6.058m x 2.438m plan x 2.591m high.

The dimensions of a transport package carried by rail shall not exceed 2.67m wide or 2.40m high.

The external dimensions of waste packages must be such that will permit them to be safely and efficiently handled using the systems defined for transport to and emplacement in a GDF.

Waste packages could be transported to a GDF by road, rail, sea or inland waterway, or by a combination of these means. In general, transport by rail is the most restrictive from the point of view of transport package external dimensions. The maximum overall dimensions of a transport package, including any covers, is set by a requirement to be compliant with the relevant 'rail gauge'. To permit the use of a large proportion of the UK rail network the GTSD uses the Standard W6A Rail Gauge [22] as the basis for defining a maximum overall envelope for transport package (including protective covers) of 2.67m wide by 2.40m high. Restrictions will also exist for the length of transport packages although these will be less onerous than those on width. Less restrictive rail gauges exist although this could limit which parts of the network could be used. Larger waste packages could also be transported by road; although the transport of larger waste packages in this manner may ultimately be limited by weight restrictions (see Section 4.3.2).

The current generic designs for a GDF, as defined in the Generic Disposal Facility Designs (GDFD) report [23] assume a maximum transport package dimensional envelope of 6.058m x 2.438m plan x 2.591m high, the limiting factor being the capability of the drift access to transfer transport packages underground. Transport by rail therefore places the bounding limit on the height of transport packages.

As discussed above, unshielded waste packages will be transported in SWTCs and therefore the bounding dimensions for transport defined above will not apply directly to them. RWM is currently developing designs for a range of SWTCs with different thicknesses of shielding to permit the safe and efficient transport of unshielded waste packages. Of the three currently anticipated designs of SWTC the SWTC-150 has the largest cavity size and could accommodate waste packages with dimensions of up to 1.85m plan by 1.37m high. However, for waste packages requiring greater radiation shielding than that provided by the SWTC-150 the SWTC-285¹¹ would have to be used, thus limiting waste package dimensions to 1.72m plan by 1.245m high. These latter values are used to define the external dimensions of the current range of unshielded waste packages, as shown below. The dimensions of the MBGWS box are such that it can only be carried using the SWTC-150, thus limiting the shielding available for such waste packages to 150mm.

The maximum external dimensions of the existing designs of waste container for use in the manufacture of unshielded waste packages (Table 1) are primarily based on the internal dimensions of the SWTC-285¹² and, in the case of the 500 litre drum, for compatibility with the stillage designs used for transport and/or disposal. The payload volumes of the three containers will depend on their precise design, the values in Table 1 assuming full use of the envelope defined by the maximum specified external dimensions.

¹¹ The SWTC-285 is assumed to be the default choice of transport container for the current range of unshielded waste packages and its relevant properties (i.e. dimensions, tare weight and shielding thickness) are used in the definition of the WPS for those waste packages.

¹² And the SWTC-70 which has the same cavity dimensions.

Table 1 Maximum dimensions and payload volumes of unshielded waste packages

Waste container type	Diameter/plan (m)	Height (m)	Approximate payload volume (m ³)
500 litre drum	0.800	1.230	0.5
3 cubic metre box - side lifting variant	1.720	1.245	2.7
3 cubic metre box - corner lifting variant	1.720	1.245	2.8
3 cubic metre drum	1.720	1.245	2.2
MBGWS box	1.853	1.372	3.6

4.1.2 Handling feature

The waste package shall enable safe handling by way of the transport and GDF handling systems.

The waste package shall incorporate handling features to enable lifting under a load equivalent to twice the maximum specified gross mass without any effect that would render it non-compliant with any of the requirements defined in the Generic Specification.

The waste container shall incorporate tie-down features suitable for the maximum gross mass specified for the waste package.

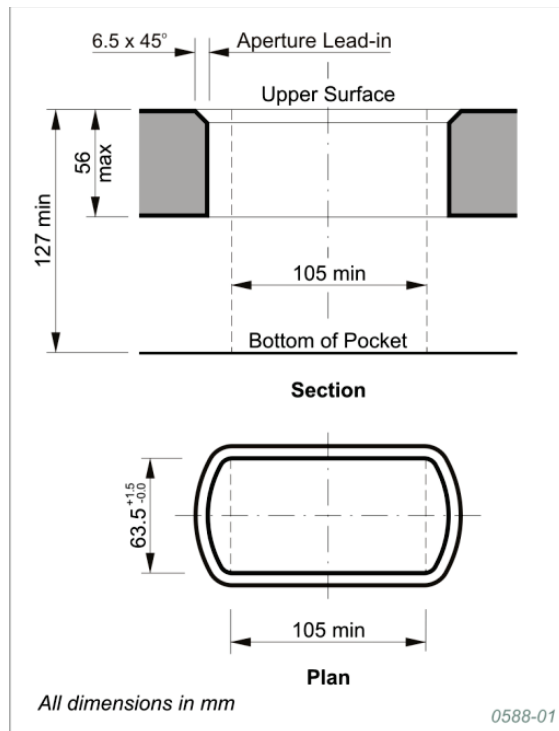
The design of the waste package should enable remote handling.

To permit the safe and efficient handling of waste packages, all waste containers are required to incorporate handling features designed in such a manner to be compatible with the handling systems that are currently assumed in the generic transport and GDF designs [23, 24].

The handling features defined for unshielded waste packages must be able to withstand the full range of forces which could be applied during normal waste package lifting operations. This includes a requirement for them to be able to withstand the loads that would result from the lifting of a waste package of twice the specified maximum gross mass, in an equi-spaced three-point lift, to take into account the so-called 'snatch factor' [25]. It is assumed that all unshielded waste packages will be remote handled at all stages of their long-term management and this should also be considered when handling features are being designed.

To enhance safety during the GDF operational period it is desirable that the number of different designs of waste package handling features should be minimised and that different designs of waste container should incorporate a common design of handling feature where practicable. To promote such an approach, ARWMA has defined a standardised design of handling feature, in the form of a 'twistlock' aperture [26], as shown in Figure 12.

Figure 12 Standardised twistlock dimensions and geometry



Operational requirements at waste packaging sites has led to two variants of the standard twistlock aperture; for the corner lifting variant of the 3 cubic metre box and the MBGWS box, as shown in Figure 13 and 14 respectively.

Figure 13 Twistlock aperture for corner lifting variant of the 3 cubic metre box

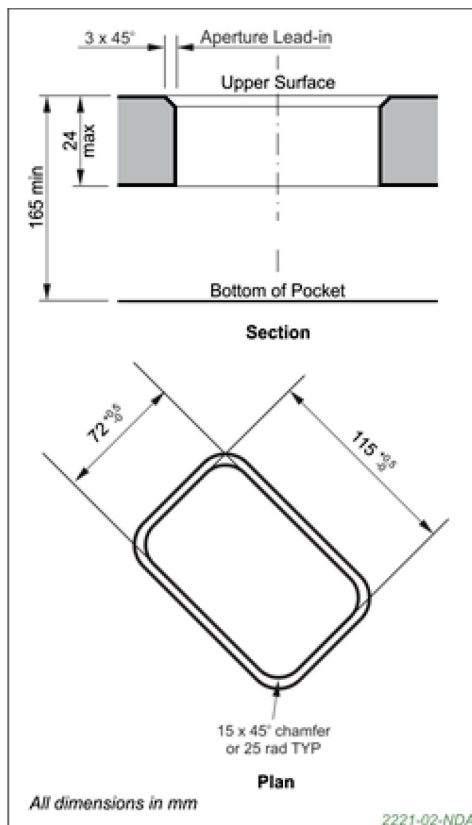
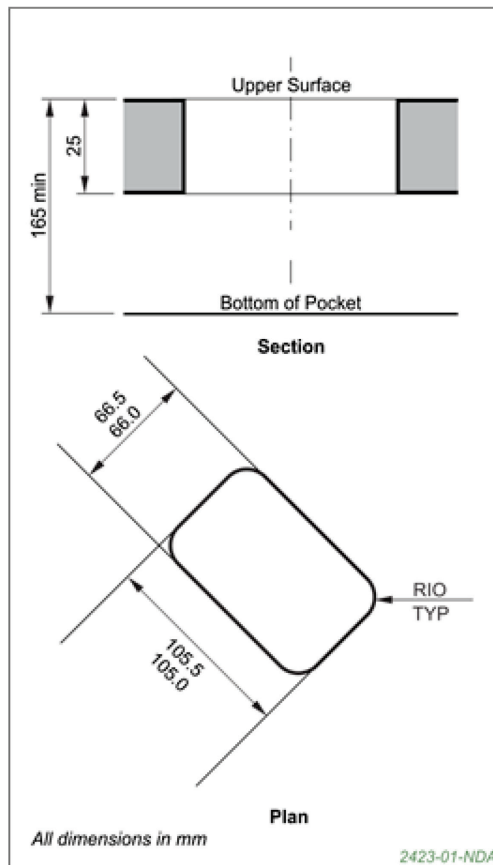


Figure 14 Twistlock aperture for the MBGWS box



The WPS for both variants of the 3 cubic metre box, the 3 cubic metre drum and the MBGWS box specify four twistlocks, located as shown in Figure 15 to 17.

Figure 15 Layouts of twistlocks for variants of the 3 cubic metre box

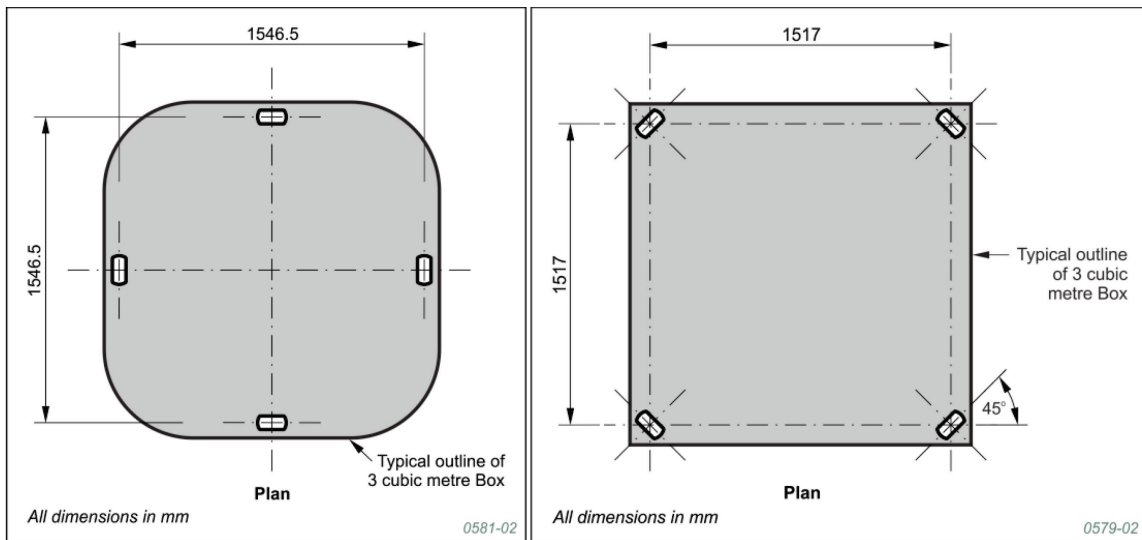


Figure 16 Layout of twistlocks for 3 cubic metre drum

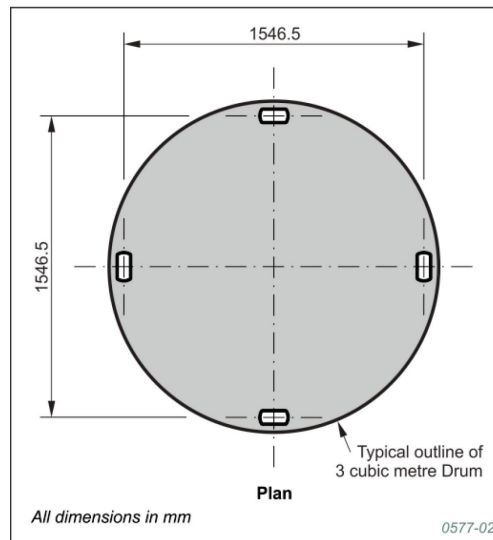
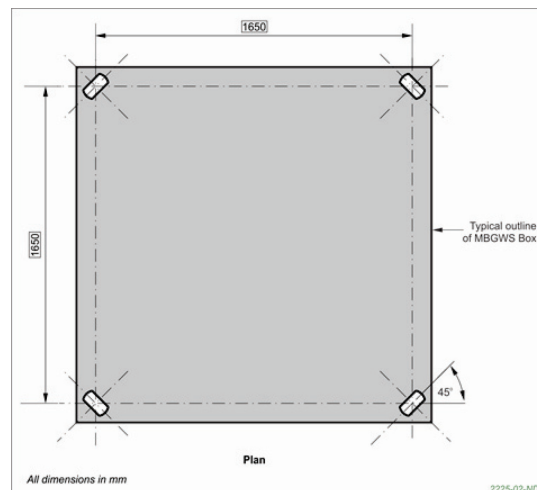


Figure 17 Layout of twistlocks for MBGWS box



During the GDF operational period all designs of unshielded waste packages (and stillages containing 500 litre drums) will be handled using a top-lift spreader. To comply with requirements at a GDF, each twistlock point must be designed to withstand the loads that would result from the lifting of a waste package of twice the specified maximum gross mass.

Whilst 500 litre drum waste packages are expected to be handled using stillages¹³, the WPS specifies a handling feature for the waste package, to permit the handling of individual waste packages (Figure 18). The anticipated use of a three claw grab for the lifting of such waste packages [27] leads to a requirement for a clear area on the upper surface of the waste package, as shown in Figure 19.

¹³ The stillage used for the handling, transport and stacking of 500 litre drum waste packages has the same twistlock layout as that specified for the corner-lifting variant of the 3 cubic metre box (i.e. the right hand diagram in Figure 15).

Figure 18 Lifting feature for 500 litre drum waste package

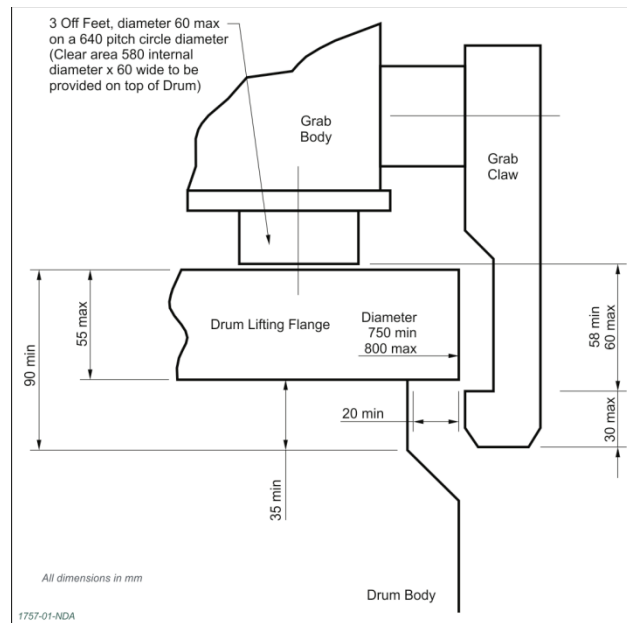
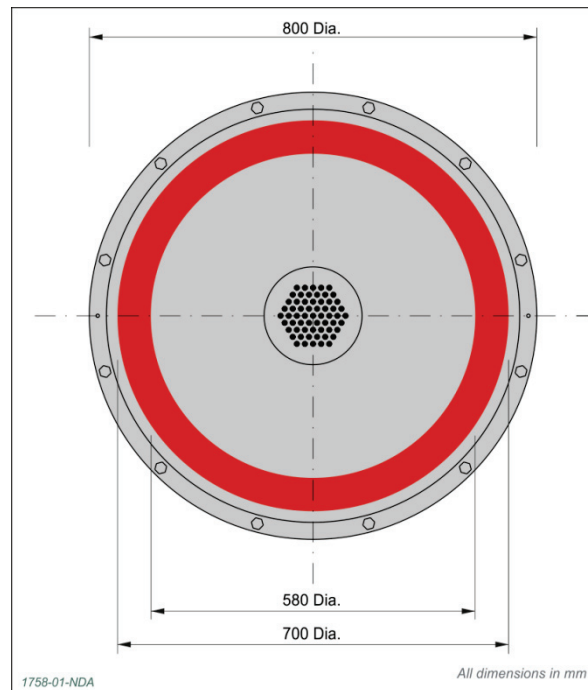


Figure 19 Required clear area on lid of 500 litre drum waste package



Each waste packager will also need to consider the lifting requirements at its own site, but must comply with the relevant RWM packaging specification as a minimum.

For some of the standardised designs of unshielded waste container the lifting feature will also play a significant role in the stacking of waste packages (Section 4.1.3) and that the design of the feature will need to take this into account.

4.1.3 Stackability

Where required by the transport or disposal system, the waste package shall enable safe stacking.

Waste packages which rely on their design to withstand stacking loads should be capable of being stacked to a height of 11m with other waste packages of the same design, each with their maximum specified gross mass. This loading shall not result in any effect that could render the waste package non-compliant with any of the requirements defined in the relevant WPS.

Waste packages containing LHGW will need to be capable of being stacked, as would be required by the design of the GDF, without suffering any deleterious effects that could threaten their safe onward long-term management.

Waste packages will be stacked in the disposal vaults to a maximum height governed by the ability to excavate vaults in a specific geological environment, whilst leaving sufficient clearance for any emplacement equipment (e.g. overhead cranes). The GDFD report [23] identifies achievable heights for disposal vaults in different geological environments and these lead to the maximum waste package stack heights for unshielded waste packages shown in Table 2. This shows that the maximum stack height for unshielded waste packages in a GDF constructed in a higher strength rock environment would be approximately 8.7m which leads to a requirement for the tallest waste packages which could be carried in a SWTC-285 (i.e. up to 1.245m high) being stacked up to 7-high and up to 6-high for those which could be carried in a SWTC-150 (i.e. up to 1.37m high).

Table 2 Stack heights for unshielded waste package in GDF vaults constructed in different geological environments

Geological environment	Estimated maximum height of disposal vault (m)	Estimated maximum stack height for unshielded waste packages (m)
Higher strength rock	16.0	8.7
Lower strength sedimentary rock	11.5	6.1
Evaporite rock	5.0	3.7

In order that waste packages of the same basic type, but containing different wastes can be stacked together, all such waste packages must be able to withstand the maximum stacking load, that corresponding to the waste package being located at the bottom of a stack of waste packages, each with the maximum specified gross mass:

- 3 cubic metre box waste packages: 6 x 12t corresponding to a load of 720kN
- 3 cubic metre drum waste packages: 6 x 8t corresponding to a load of 480kN
- MBGWS box waste packages: 5 x 12t corresponding to a load of 600kN

Under these conditions, the waste packages should not exhibit any permanent deformation or abnormality that would render it incompatible with any of the requirements defined in the relevant WPS.

No stacking requirement is specified for the 500 litre drum waste package as the stillage will be designed to withstand all loads resulting from stacking.

Although the ability to be safely stacked without deformation is a necessary characteristic of the waste package as a whole, it is considered good practice to allocate this requirement, where feasible, to the waste container (or stillage where this is used) and to claim no benefit from support provided by the wasteform [28]. This is on the basis that a waste container can be designed and manufactured to provide the required load bearing performance for the required period of time whereas the longer-term strength of a wasteform, not primarily designed for load bearing, cannot be assured with the same degree of confidence.

The stacking elements of a waste package design must take into account timescale and ageing of the waste package, especially the components of the waste package that will take the stacking load. Yield strength, stiffness and creep resistance are material properties expected to control the stacking performance of a container material and the thinning of the container material (i.e. due to corrosion) will also have to be taken into account. A method for assessing the suitability of a candidate material for the fabrication of waste containers, from the point of view of waste package stacking, can be found in [29].

Waste packagers may choose to stack waste packages higher than the GDF stack heights during interim surface storage, but must ensure that after having been stacked in such a manner for an extended period¹⁴ the waste packages will still meet the requirements of the relevant WPS for dimensional envelope and the handling features.

4.1.4 Identification

The waste package shall enable unique identification until the end of the GDF operational period.

The waste package shall be marked at multiple defined locations with a unique alpha-numeric identifier.

The waste package shall remain identifiable by automated systems for a minimum period of 150 years following manufacture.

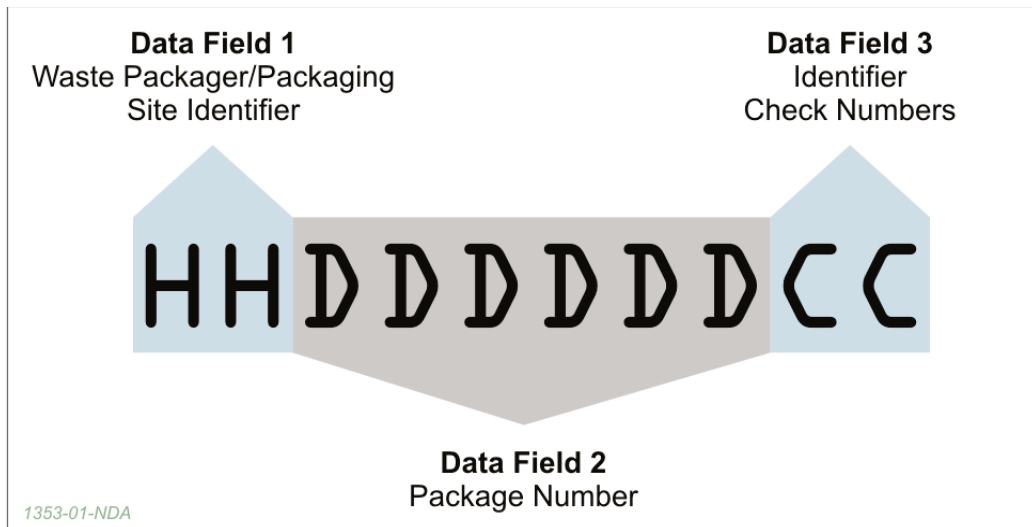
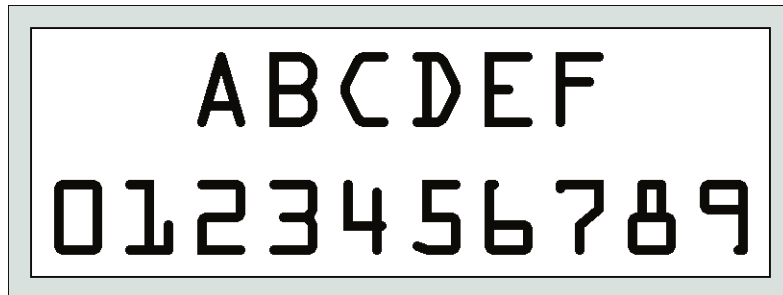
The application of a unique identifier enables the identification and tracking of every waste package throughout the different stages of its long-term management¹⁵, and permits the permanent assignment of the appropriate data record to that waste package.

RWM has defined an identifier format consisting of ten alpha-numeric characters (Figure 20), which includes 'check numbers', to help minimise the possibility of loss of waste package identification over the required period [30]. The use of a standard character set (i.e. OCR-A characters, Figure 21, [31]), of a specified size (i.e. 6-10mm high) will permit either direct visual checking by human operators or the use of automated reading equipment. Making the identifier machine-readable and the use of a format containing check digits allows the waste package to be identified remotely and its number verified by an automatic computer check.

Waste package identifiers will need to remain machine readable for a period that permits identification of the waste package at least until the time at which it is surrounded by the backfill material. In defining a durability timescale for identifiers, RWM applies the same arguments as those used to justify the required durability of waste container integrity (see Section 4.1.5). These lead to a minimum period of 150 years following manufacture during which the waste package shall remain capable of being identified.

¹⁴ For consistency with the identification and durability of integrity requirements for waste packages (see Sections 4.1.4 and 4.1.5) a period of 150 years should be assumed.

¹⁵ In practise this requirement would only need to extend up to the end of the GDF operational period as after backfilling of the disposal vault the requirement to identify waste packages would be expected to cease.

Figure 20 Form of waste package identifier**Figure 21 Character set for waste package identifiers**

For automated reading systems to operate effectively, standard locations must be specified for identifiers. Multiple locations will aid in the ease of reading by reducing the need for the waste package to be moved during identification as well as providing redundancy in the event of damage (for example that caused by corrosion) and will reduce the risk of waste packages becoming unidentifiable. The specified locations for identifiers on the three unshielded waste package designs are shown in Figure 8 to 11.

The locations specified for identifiers on the existing designs of unshielded waste packages have been selected in such a manner as to reduce the need for the waste package to be moved in order for it to be identified and also minimise the possibility of the identifier being obscured by handling equipment. The locations have also been selected such that they are on thicker sections of the waste container, to reduce any deleterious effect on the durability of the containment function of the waste container.

The recommended method of inscribing the identifier is to laser-etch the characters, which in the case of stainless steel surfaces is expected to satisfy the requirement specified for the longevity of the marking.

In-house markings and additional labels may be applied by the waste packager if required for its own purposes, provided that they do not affect package performance. In particular, any additional identification, whether temporary or permanent, must not compromise the integrity or containment of the package. This should include a consideration of the materials used for such markings, guidance on which can be found in [32].

4.1.5 Durability of waste container integrity

The waste package shall enable safe handling by way of its handling feature until the end of the GDF operational period.

The waste container shall maintain containment for as long as is required by the GDF safety case.

The integrity of the waste container should be maintained for a period of 500 years following manufacture of the waste package.

In Section 2.2 the safety functions that are required of waste packages, and that are identified in the GWPS [2], were discussed in the context of waste packages containing LHW. For most designs of waste package those safety functions will be provided by a combination of contributions from both the waste container and the wasteform, the degree of contribution made by each being dependent on the particular design of the waste package (Figure 1).

Two of the operational safety functions (i.e. for containment and safe handling) rely heavily on the maintenance of the integrity of the waste container for a given period. Other safety functions, such as the ability of the waste package to withstand external loads will also rely at least in part on such integrity. The requirement for the durability of waste container integrity is therefore defined in terms of the period for which the waste container needs to maintain the containment of its contents, the surety of its handling features and its ability to withstand all anticipated external loads, notably those resulting from stacking.

Regulatory guidance on the conditioning and disposability of higher activity waste states that '*A minimum package lifetime of 150 years should be set for design purposes*' [33]. Such a period broadly aligns with current planning assumptions regarding when a GDF would be available to receive waste packages for disposal (i.e. 2040) and the anticipated length of the GDF operational period (assumed in the GDFD to be ~100 years [23]).

The potential for the retrieval of waste packages from the disposal vaults also needs to be considered when defining the period over which the integrity of the waste container is required to be maintained. RWM's current position on retrievability is that activities concerned with the development and implementation of a GDF will be carried out in such a way that the option of retrievability is not excluded [34]. The UK Government's policy regarding retrievability is outlined in the 2014 White Paper [1] which states that waste packages could be retrieved during the GDF operational period '*if there was a compelling reason to do so*', whilst acknowledging that a GDF '*could be open for construction and waste placement for around one hundred years, to accommodate the current volume of legacy waste*'. The White Paper also notes that retrieving emplaced waste packages '*would tend to become more difficult with time, particularly after the end of its operational stage (that is, once a GDF has been closed permanently)*'.

The DSTS defines a number of safety functions that the waste container will be required to provide for waste packages in the post-closure period. These include restricting the access of groundwater to the wasteform, as a means of delaying the release of radionuclides into the other components of the EBS. In the case of waste packages containing LHW this refers notably to the retention of relatively short-lived water soluble radionuclides (e.g. strontium-90 and caesium-137, each with half-lives of ~30 years). Whilst indefinite retention of such radionuclides is not the aim, the waste container should provide an effective barrier for a period that would permit them to decay to relatively insignificant levels before their release.

In order to satisfy the potential requirements of both the operational and early post-closure periods, the need to maintain waste container integrity for 500 years, as specified in the

2007 GWPS¹⁶ [35], has been retained. RWM has carried out work which shows that current designs of waste container, designed to meet the durability requirement identified by regulatory guidance (i.e. 150 years), would also be expected to maintain an appropriate level of integrity for at least 500 years [36]. Notwithstanding this, RWM acknowledges that after 150 years waste packages may need to be handled by means which do not involve the use of the integral handling feature.

The ability of a specific design of waste container to meet this durability requirement will be assessed by way of the Disposability Assessment Process which, as well as considering the design of the waste container itself, will also take into account the potential consequences of the contents of the waste package for the durability of waste container integrity.

The ability of a waste container to maintain its integrity over a specified period is controlled by a number of key factors:

- the design of the waste container, including the materials and manufacturing processes;
- the nature of container material degradation mechanisms;
- the nature of any interactions between the waste container and the wasteform; and
- the environment of storage and disposal facilities.

Corrosion is the major potential threat to the ability of a waste container to maintain an adequate level of integrity for the required timescale. Other mechanisms of degradation can include the effects of heat, biodegradation, abrasion, radiolysis and chemical reactions between waste container components.

When selecting a material for the fabrication of waste containers, waste packagers will need to understand both the internal and external environments that a container will be subjected to, and determine which degradation mechanisms can take place in those environments. The response of waste packagers to this requirement has generally been to manufacture waste containers from austenitic stainless steel to grade 316L (EN 1.4404 [37]) or its equivalent. The corrosion performance and mechanical properties of this material are generally regarded as optimum for the packaging of radioactive waste, and this performance has been demonstrated by experience and research [21]. 'Duplex' stainless steel (notably grade EN 1.4462) has been identified as an alternative material that has the necessary corrosion performance to make it suitable for the manufacture of waste containers. Whichever material is selected it should be noted that quality control of the material, the container manufacturing process and the control of surface finish of the material will also play key roles in maintaining the integrity of the waste container.

A variety of corrosion mechanisms can threaten the integrity of waste containers manufactured from stainless steel, the most significant of which are; general atmospheric corrosion, pitting or crevice corrosion and stress corrosion cracking.

The rate of general atmospheric corrosion performance of stainless steel are widely reported [38] and corrosion rates from $<0.2\mu\text{my}^{-1}$ ($>5,000\text{y}\text{mm}^{-1}$) to $3\mu\text{my}^{-1}$ ($300\text{y}\text{mm}^{-1}$) have been observed in industrial/urban and marine environments. Initial measurements from longer-term testing suggest corrosion rates of $\sim 0.01\mu\text{my}^{-1}$ ($100,000\text{y}\text{mm}^{-1}$) are more typical for a GDF environment which, when applied to waste container sections of a few mm, would suggest that such a mechanism is not a significant threat to integrity.

Localised corrosion mechanisms such as pitting or crevice corrosion, tend to be considered a greater threat to stainless steel waste containers than general corrosion. Nevertheless,

¹⁶ This document has since been replaced by the Generic Specification for waste packages containing LHGW [3]

data extrapolated from tests [39, 40] have shown that the time for a pit to penetrate 1mm into 316L stainless steel is many centuries. Crevices formed between waste container components, in the container lid area and in between the wastefrom and the inside of the container should be avoided during waste container and waste package design. Localised corrosion mechanisms are also dependent upon the presence of surface contaminants, in particular, chlorides. Work has been carried out to investigate these effects and to specify requirements for, amongst other factors, the surface finish of stainless steel used for waste containers [41].

The incidence of atmospheric stress corrosion cracking is dependent on the presence and concentration of soluble chloride deposits, the chemical form of the chloride, temperature, relative humidity and the metallurgical state of the stainless steel [38]. Such corrosion of stainless steel can be accelerated at temperatures above 60°C but may also be significant at lower temperatures. The chloride content of wasteforms should therefore be kept to a minimum and careful consideration given to possible corrosion mechanisms if it exceeds 100ppm. Consideration should be given to mechanisms for the generation of chloride ions by the wastefrom, for example by the radiolysis or thermal breakdown of chlorine-containing plastics. A pre-requisite for this type of localised corrosion is access by oxygen to the surface of the container material. Accordingly the elimination or reduction of internal voidage, ullage or gaps between the wastefrom and the waste container inner surface, to reduce oxygen access, is of benefit, and will also reduce the possibility of water condensation on internal surfaces.

Intergranular corrosion or 'weld decay' can occur in austenitic stainless steel that has been 'sensitised' by the high temperatures experienced during welding. The risk of sensitisation is minimised by use of low carbon or stabilised grades of stainless steel. Nevertheless, excessively high heat inputs should be avoided, as should contamination of the weld by materials containing carbon or nitrogen.

The following matters should be taken into account during the design of a waste container, and the wastefrom it contains:

- A high pH environment is generally considered to be beneficial in reducing corrosion rates; accordingly a wastefrom that does not promote such conditions could accelerate corrosion.
- Corrosion inside the waste container can also be accelerated by electrolytic action with dissimilar materials, or with other aggressive components that may be present in the package. Particular consideration should be given to preventing the possibility of metal items in the wastefrom from contacting the container walls directly.
- The presence of microbes, together with the right conditions of nutrient and water supply on a waste container surface, could also lead to the microbially induced corrosive degradation of the material.
- Stored waste packages will emit and be exposed to gamma radiation from within and from surrounding packages. A consequence of such exposure is to produce nitric acid from atmospheric nitrogen, oxygen and water. Minimisation of the presence of free water, or water readily available in the vapour phase, will reduce the quantity of nitric acid that could be produced.
- Radiolysis of waste package contents can result in the production of aggressive chemicals (e.g. hydrochloric acid from the radiolysis of polyvinyl chloride) that accelerate degradation processes.

To assist waste packagers in these areas, guidance has been produced on the general corrosion properties of stainless steel [21], the requirements for surface finish [41] and on welding techniques used during the manufacture of stainless steel containers [42].

4.2 Requirements for wasteforms

The properties of the wasteform shall be such that, in conjunction with those of the waste container, it satisfies all of the requirements for the waste package.

The properties of the wasteform shall comply with the requirements for containment within the geological disposal concept, as defined by the GDF safety case.

The physical, chemical, biological and radiological properties of the wasteform shall:

- make an appropriate contribution to the overall performance of the waste package; and
- have no significant deleterious effect on the performance of the waste container.

Evolution of the wasteform shall ensure maintenance of the waste package properties that are necessary for safe transport and operations at a GDF.

Evolution of the wasteform shall ensure maintenance of the required safety functions for post-closure performance as set out in the ESC.

As discussed in Section 2.2 the required performance of a waste package will be provided by a combination of the properties of the waste container and the wasteform it contains. For unshielded waste packages both the waste container and the wasteform will play a role in ensuring passive safety of the waste package. Wastes should therefore be conditioned to minimise chemical reactivity and to satisfy some basic requirements as to their physical and biological properties. This should extend to ensuring the compatibility of the wasteform and the material from which the waste container is fabricated (see Section 4.1.5).

These general requirements for wasteforms can be achieved by sorting, segregation and/or a range of pre-treatment processes to ensure the appropriate control of the quantities of some types of material, or of wasteform properties, that could affect the overall performance of the waste package or the other barriers that make up the geological disposal system. Typically this could include controls on the presence of:

- free liquids;
- activity or hazardous materials in particulate form;
- voidage;
- in-homogeneity;
- reactive materials;
- other hazardous materials¹⁷; and
- materials that could have a deleterious effect on the other barriers that make up the EBS.

The extent of such controls will be very dependent on the robustness of the waste container and the consequences of the presence of these materials and wasteform properties for waste package and disposal system performance. This would normally be assessed as part of the disposability assessment of a proposed waste package design.

The wasteform will play a key role in the immobilisation of the radionuclides associated with the waste it contains. Immobilisation is defined as the adequate elimination of the freedom of movement of radionuclides within a wasteform and can be achieved by rendering waste

¹⁷ Hazardous materials include flammable, explosive, pyrophoric, chemo-toxic and oxidising materials, sealed containers and objects containing stored energy.

into a solid monolithic form, typically by the use of a cementitious or polymeric encapsulating medium.

Evolution of the wasteform, resulting from chemical, biological and/or radiation induced processes will change the properties of the wasteform with time. It is important that such evolution will not result in changes that render the waste package incompatible with the needs of transport or the requirements for safety in the GDF operational period.

In the post-closure period the wasteform may continue to play a role in the overall safety of a GDF. The DSTS defines the post-closure safety function of the wasteform as requiring it to *'provide a stable, low-solubility matrix that limits the rate of release of the majority of radionuclides by dissolution in groundwater that comes into contact with the wasteform'*. Accordingly the consequences of evolution should be such that this requirement is satisfied and that the wasteform will continue to make an appropriate contribution to the overall performance of the waste package, and to the geological disposal system as a whole.

The role of the wasteform in helping to ensure adequate waste package performance, and the manner in which wasteform performance can be achieved, is discussed in detail in the wasteform guidance that complements this Guidance (i.e. [6, 7]).

4.3 Requirements for waste packages

4.3.1 Activity content

The activity content of the waste package shall be controlled to comply with the radionuclide related assumptions that underpin the safety cases for transport and the GDF operational period.

For waste packages transported as part of a Type B transport package, or as Type B transport packages in their own right the total activity content of the transport package should not exceed $10^5 A_2$.

The activity content of an unshielded waste package transported as part of a Type B transport package will be subject to a number of indirect controls that are placed by one or more of a number of radionuclide related parameters. These are dealt with separately in the packaging specifications and comprise:

- External dose rate (Section 4.3.3)
- Heat output (Section 4.3.4)
- Criticality safety (Section 4.3.7)
- Accident performance (Section 4.3.8)

The IAEA Transport Regulations limit the activity contents of Type B transport packages which have not been qualified to satisfy the requirement of an 'enhanced water immersion test' (Paragraph 730) to $10^5 A_2$. It is believed that the current designs of SWTC would be capable of satisfying this requirement; accordingly this activity limit would not apply to the unshielded waste packages they would be expected to carry.

4.3.2 Gross mass

The gross mass of the waste package shall be compatible with the transport and GDF handling systems and with the requirement for the waste package to be safely stacked.

The gross mass of a transport package should not exceed 65t.

The gross mass of waste packages must be such that will permit them to be safely and efficiently handled using the systems defined for transport to and emplacement in a GDF. The gross masses of transport packages must also be compatible with the UK transport

infrastructure such that no undue limits are placed on the mode of transport that can be used (i.e. by road, rail, sea or inland waterway).

The GDFD currently includes a number of assumptions regarding the safe working loads (SWL) for the GDF lifting and handling equipment. This includes a capability to transfer underground and subsequently handle transport packages with gross masses (including any handling equipment such as lifting frames) of up to 80t. For unshielded waste packages the handling equipment that will be used to remove them from the SWTC, transfer them to the disposal vaults and stack them, will have SWLs of 20t.

For transport by rail, the GTSD [24] currently assumes the use of a four-axle wagon, which would allow transport packages with gross masses of up to ~64t to be carried on a large proportion of the UK rail network. The possibility does exist for the use of eight-axle rail wagons capable of carrying greater loads but these may only be suitable for use on a reduced proportion of the rail network.

For transport by road, the maximum permitted laden mass of an ordinary heavy goods vehicle (HGV) is 44t which, when an allowance is made for the mass of the vehicle itself, sets a limit of ~30t for the load. Transport packages with gross masses of greater than 30t will require special transport arrangements and there may therefore be operational benefits in maintaining transport package masses below this value.

In the case of all existing unshielded waste package designs the bulk of the mass of a transport package will be that of the SWTC. Table 3 lists the maximum transport packages that would result from using each of the three SWTC variants to carry the existing unshielded waste package designs, assumed to have the maximum specified mass.

Table 3 Gross masses of SWTC/unshielded waste package combinations

SWTC variant	Unladen mass (t)	Maximum mass of transport package (t)			
		500 litre drum	3 cubic metre box	3 cubic metre drum	MBGWS box
SWTC-70	18	27	30	26	-
SWTC-150	28	37	40	36	40
SWTC-285	52	61	64	60	-

Two potential means by which unshielded waste packages with gross masses of greater than 12t could be transported by rail in a SWTC:

- (i) The use of eight-axle rail wagons capable of carrying greater loads than 64t, although such wagons may not be able to be used over the whole of the UK rail network; and
- (ii) The use of less heavily shielded variants of the SWTC with lower unladen masses (i.e. the SWTC-70 and the SWTC-150).

Table 3 shows that only the SWTC-70, with an unladen mass of 18t, is suitable for the transport of unshielded waste packages by road without special arrangements, since the maximum gross mass of the transport package would not exceed 30t.

The ability of waste packages to be safely stacked can place a more onerous limit on waste packages maximum gross mass. Current designs of both variants of the 3 cubic metre box include stacking pillars which bear stacking loads and thereby permit such waste packages to have gross masses of up to 12t. However, in the case of the 3 cubic metre drum the

lifting/stacking features form part of the top surface of the container (see Figure 4) and the container would not be able to provide sufficient strength to resist the stacking load that would result from 7-high stacking of 12t waste packages without significant reliance of the properties of the wasteform. Accordingly a gross mass limit of 8t is specified for 3 cubic metre drum waste packages. In the case of 500 litre drum waste packages, the 2t 'limit' reflects the expected use of the container in that it is unlikely that such waste packages would have gross masses of much greater than ~1t.

4.3.3 External dose rate

The external dose rate from the waste package shall enable safe handling of the waste package during transport and the GDF operational period, and shall comply with regulatory limits for transport.

The external dose rate of the waste package should be compatible with the dose rate at 1 metre from any external surface of a transport package, under normal conditions of transport, not exceeding 0.1mSvh^{-1} and the dose rate on its external surface not exceeding 2mSvh^{-1} .

Limits on waste package external dose rates are specified to ensure that routine radiation doses to transport and GDF workers, as well as to members of the public, are as low as reasonably practicable (ALARP) and less than the relevant regulatory limits.

The IAEA Transport Regulations define limits for the external dose rate from transport packages which depend on the operational controls under which transport operations are carried out (i.e. whether under the conditions of 'exclusive use' or 'non-exclusive use'). The more stringent of the limits, those for non-exclusive use, have been adopted as the limiting values for all transport packages in the GTSD [24] and the Transport Safety Case (TSC) [43]; they are therefore also adopted in this Guidance. These limits require that transport package dose rates are no more than:

- 2mSvh^{-1} on the external surface; and
- 0.1mSvh^{-1} at 1m from the external surface.

The possibility to transport unshielded waste packages as part of transport packages with higher radiation levels exists if they were carried under the conditions defined for exclusive use. Under such conditions the external dose rate limits are:

- 10mSvh^{-1} on the external surface; and
- 0.1mSvh^{-1} at 2m from the external surface.

It should be noted that transport packages with external dose rates in excess of those defined for the conditions of non-exclusive use will have consequences for worker dose during interim storage at the site of arising, transport and during the GDF operational period, and for the respective safety cases. The waste packager will need to consider the former to ensure that the dose consequences of the packaging of the waste and the interim storage of the waste packages are ALARP, whilst those of the latter two periods (i.e. transport and GDF operations) would be considered as part of the disposability assessment of the proposed waste packages.

By their nature the designs of the containers used for unshielded waste packages do not generally incorporate significant radiation shielding although in some cases 'self-shielding' by components of the waste and/or any conditioning materials can reduce the external dose rate from a waste package. The extent of such shielding can be enhanced by the use of conditioning materials which includes high density components such as iron oxide or lead shot.

The maximum permitted external dose of an unshielded waste package will depend on the thickness of the shielding provided by the transport container. The WPSs assume the use of the SWTC with the greatest shielding thickness (i.e. the SWTC-285 which provides

shielding of 280mm of mild steel), although the use of the thickest, and therefore heaviest, SWTC may not always be the best approach. This is notably the case for where no on-site railhead exists and transport packages will be required to make at least part of the journey by road. In such cases the SWTC-70 may have to be used to ensure that the transport package mass falls below the 30t limit for road transport using an ordinary HGV. In such cases the external radiation from the 'bare' waste package would have to be limited to ensure that 70mm of shielding would be sufficient to ensure that the transport package external dose rates are not exceeded.

4.3.4 Heat output

The heat generated by the waste package shall be controlled to ensure that:

- ***thermal effects result in no significant deterioration in the performance of the waste package, or of the disposal system as a whole; and***
- ***regulatory limits on the surface temperature of transport packages are not exceeded.***

The heat output of the waste package at the time of disposal vault closure should not exceed 6 watts per cubic metre of conditioned waste.

The most significant source of heat generation in most radioactive waste is radiogenic heat. In general the radiogenic heat output of the wastes described as LHW that are expected to be packaged using unshielded waste packages will be low, having an average heat output of ~1.1W per cubic metre of conditioned waste in 2040, declining to ~0.5Wm⁻³ by 2090 [44].

Some ILW waste streams have heat outputs significantly higher than the average values and the activity concentrations within some waste streams are very heterogeneous and this could lead to individual waste packages with heat outputs which are significantly higher than the average. There are also some types of LHW which have significantly higher radiogenic heat outputs.

Heat generation by non-radiogenic mechanisms can also be significant for some LHW and could amount up to 3Wm⁻³ due to the corrosion of metals in wastes, and up to 2Wm⁻³ from the microbial degradation of materials such as cellulose [45].

Transport

The IAEA Transport Regulations define qualitative and quantitative controls on the heat generated by the contents of transport packages. For all transport packages these include ensuring that *'the design of the package shall take into account ambient temperatures that are likely to be encountered during routine conditions of transport'* (Paragraph 616).

Additional requirements are specified for Type B transport packages including an assurance that internal heat generation will not alter *'the geometrical form or the physical state of the radioactive contents'* or *'lessen the efficiency of the packaging through differential thermal expansion, or cracking, or melting of the radiation shielding material or, in combination with moisture, accelerate corrosion'* (Paragraph 653).

Paragraph 654 specifies a maximum temperature of 50°C for any accessible surface of a Type B transport package carried under the conditions of non-exclusive use. Paragraph 655 specifies additional operational controls for the stowage and storage of transport packages that have an average surface heat flux of greater than 15Wm⁻².

Thermal modelling of a typical Type B transport package containing unshielded waste packages¹⁸ has shown that a total heat output of 200W would not result in a transport package surface temperature in excess of 50°C[46]. More recent work on Type B transport

¹⁸ A SWTC-70 containing four 500 litre drum waste packages.

packages has indicated that the ultimate transport limit for the heat generated by the contents of a SWTC-285 is in excess of 400W [47].

GDF operational and post-closure periods

The DSTS specifies a limit of 50°C for the air temperature in the GDF disposal vaults. This is specified to limit the deterioration of the waste package, to protect GDF systems such as electrical equipment and high efficiency particulate in air (HEPA) filters, and to permit human access to relevant areas.

RWM has commissioned thermal modelling of various designs of disposal vault to investigate the thermal performance of waste packages during the operational period [48, 49]. This has shown that, for disposal vaults containing large arrays of waste packages with an average waste package heat output of 6Wm^{-3} , a maximum package temperature of 35°C would occur.

The DSTS also specifies temperature targets for the GDF disposal vaults in the post-backfilling period specifically to reduce the consequences of heat on the GDF engineered barrier system. This could result from accelerated evolution of the waste packages or chemical changes in any disposal vault backfill material. The curing of such material may be accompanied by the release of significant quantities of chemical energy which will result in the temporary (i.e. for a few years) increase in the temperature of the disposal vaults. In addition radiogenic heat will continue to be generated by the contents of the waste packages, albeit at a progressively decreasing rate.

As a means of minimising the likelihood and consequences of such effects, the DSTS defines a short-term target of 80°C, applicable to a period of a few years, and a longer-term target of 50°C which should be attained a few decades after backfilling of the disposal vaults. Thermal modelling of the backfilled vaults has shown that an average waste package heat output of 6Wm^{-3} at the time of back-filling would result in the 50°C target being exceeded for a period of ~20 years but that the short term target of 80°C would not be exceeded [50].

The heat output limits and screening levels for the existing designs of unshielded waste package are listed in Table 4.

Table 4 Heat output limits for unshielded waste packages

	Heat output (W)			
	500 litre drum	3 cubic metre box	3 cubic metre drum	MBGWS box
At time of transport	100 ¹	400	400	400
At time of emplacement ³	3 ²	20	15	25
At time of disposal vault backfilling ⁴	50	300	250	400

Notes: ¹ Assumes four identical waste packages in a SWTC.
² Assumes four identical waste packages in a stillage.
³ Average heat output for waste packages from a waste stream.
⁴ Maximum heat output for individual waste packages.

The post-backfilling period places the most constraining limits on waste package heat output, largely due to the large quantity of heat released during the curing of the backfill material and the reduction and eventual loss of ventilation in the disposal vaults. The thermal modelling which led to the definition of the screening level for waste package heat

output (i.e. 6Wm^{-3}) showed that if all of the waste packages in a disposal vault had such a heat output at the time of back-filling the long term temperature target of 50°C would be exceeded for a period of ~ 20 years but that the short term target of 80°C would not be exceeded [50]. Similar modelling with a mean heat output of 12Wm^{-3} resulted in both the short and long term targets being exceeded for extended periods. The work also showed that the inclusion of individual waste packages generating up to $\sim 100\text{Wm}^{-3}$ in a vault containing waste packages with a mean heat output of $\sim 1\text{Wm}^{-3}$ would result in localised higher temperatures but which would not exceed the short- or long-term temperature targets [51, 52].

The results of the thermal modelling suggest that flexibility exists in the application of the heat output constraints, in practise however this may not always be the case. The thermal modelling has generally been carried out with heat sources terms that are typical of ILW, where heat output is dominated in the first century following packaging by radionuclides with half-lives of up to ~ 30 years (e.g. strontium-90 and caesium-137). For wastes with a higher proportion of longer lived radionuclides the greater persistence of heat generation can significantly affect temperatures in the post-backfilling period. Also whilst the modelling has shown that individual 'hot' waste packages can be accommodated, their numbers must be small (typically no more than 1 in a few hundred) and the heat output of the surrounding waste packages low (i.e. no more than $\sim 1\text{Wm}^{-3}$) in order that excessive temperatures would not result from their presence. Accordingly if a packaging proposal would result in average heat outputs close to the screening level and/or significant numbers of waste packages with heat output greater than it, bespoke thermal modelling may be required.

Implications for waste package design

A heat output of 100Wm^{-3} would correspond to a surface heat flux from a typical unshielded waste package of up to 20Wm^{-2} . The material selected for the waste container should be capable of conducting these fluxes without causing significant temperature rise on the inner surface. As an example, if a temperature difference of 10°C across the thickness of the container wall was judged to be acceptable, for a 5mm thick wall to conduct a heat flux of 20Wm^{-2} a minimum thermal conductivity for a waste container material would be of the order of $0.01\text{Wm}^{-1}\text{K}^{-1}$. By way of context, the thermal conductivities of most metals are of the order of $100\text{Wm}^{-1}\text{K}^{-1}$. The definition of a disposal vault upper temperature target of 80°C for 'short-term excursions' also requires that the material used for waste containers should be capable of withstanding such temperatures without any significant degradation. This would include excessive thermal expansion, transition to a different solid phase change or, in extreme cases, melting of the waste container.

4.3.5 Surface contamination

The non-fixed surface contamination of the waste package shall be as low as reasonably practicable and shall comply with regulatory limits for transport.

For waste packages transported inside transport containers the non-fixed surface contamination, when averaged over an area of 300cm^2 of any part of the surface of the waste package, should not exceed:

- **4.0Bqcm^{-2} for beta, gamma and low toxicity alpha emitters¹⁹; and**
- **0.4Bqcm^{-2} for all other alpha emitters.**

Limits on the non-fixed²⁰ surface contamination of unshielded waste packages are specified to ensure that the adventitious contamination of transport and GDF systems is maintained

¹⁹ Low toxicity alpha emitters are defined by the IAEA Transport Regulations (Paragraph 227) as '...natural uranium; depleted uranium; natural thorium; uranium-235 or uranium-238; thorium-232; thorium 228 and thorium-230 when contained in ores or physical and chemical concentrates; or alpha emitters with a half-life of less than 10 days'.

below acceptable levels, and are ALARA, and that routine doses to workers and the members of the public as a result of such contamination are ALARP and in accordance with good industry practice.

Since unshielded waste packages are expected to be remotely handled and are transported in transport containers the dose consequences of the presence of non-fixed surface contamination are limited.

Unshielded waste packages are not subject to the non-fixed surface contamination limits specified by the IAEA Transport Regulations (i.e. 4.0Bqcm^{-2} for beta, gamma and low toxicity alpha emitters and 0.4Bqcm^{-2} for all other alpha emitters), however the WPS use those limits as targets for ensuring that the minimisation of surface contamination remains an objective during the manufacture of waste packages. These targets have been adopted on the basis that they represent realistic and achievable levels and will reduce any potential requirement for the decontamination of the internal surfaces of transport containers and the areas of the GDF where 'bare' waste packages are handled.

It should be noted that these targets only apply to 'non-fixed' contamination on the basis that such material could become detached from the waste package during routine operations and inhaled or ingested by humans. Contamination deemed as being 'fixed' cannot be as readily removed and therefore cannot cause dose by such mechanisms. It can however contribute to the external radiation from the waste packages and is covered by the limits discussed above. It should also be noted however that 'fixed' contamination can become 'non-fixed' as a result of the effects of waste package ageing, weather or handling and that the level of non-fixed contamination could increase with time.

Although waste packages can become contaminated at a number of stages during their long-term management, the most significant opportunity for surface contamination occurs during manufacture. The priority should therefore be to ensure that such contamination does not take place in the first place. In most instances where packages are slightly contaminated on the outer surfaces, the contamination is almost entirely removable or non-fixed. However, some contaminants such may strongly adhere to, or penetrate into, the external surfaces of waste containers. Contamination may become ingrained in pores, fine cracks and crevices, particularly in the vicinity of lid seals. Subsequent ageing of the waste package surfaces (e.g. due to corrosion) or such effects as thermal cycling or exposure to moist air, may lead to previously fixed contamination to become non-fixed.

The means by which the decontamination of waste package surfaces takes place should be carefully considered to ensure that it does not cause damage to those surfaces. The 'finish' of the surfaces of the waste container is important in this respect [41]. In general, a material with a smooth, hard, corrosion resistant surface will reduce the possibility of contamination and make any necessary decontamination more effective. The effectiveness of a decontamination method for a material with a specific surface finish can be evaluated using the 'decontamination factor' (DF), the ratio of the initial contamination of the surface to that after decontamination. 'Ease of decontamination' (ED) is a qualitative term i.e. excellent, good, fair or poor that is related to the DF value as shown in Table 5.

The main criterion affecting the ability of a waste container material to be amenable to effective decontamination is the surface texture than can be readily achieved during the manufacture of the material. The 'smoother' a material finish, the less number of locations that can harbour contamination and resist simple decontamination methods, and the lower the qualitative definition of ED. Guidance on surface texture and its measurement are given in [53,54].

²⁰ Non-fixed contamination is defined by the IAEA Transport Regulations (Paragraph 215) as '*...contamination that can be removed from a surface during routine conditions of transport.*'

Table 5 The relationship between decontamination factor and ease of decontamination

Measured DF	Corresponding ED
> 1000	Excellent
100 - 1000	Good
10-100	Fair
<10	Poor

The hardness of a material is an important property that should be considered when selecting a material for container fabrication. Harder surfaces have more resistance to abrasive damage thereby reducing the potential for surface scratching affecting the surface topography of a material, and the potential for ground-in contamination to occur during a waste treatment process. Additional chemical and mechanical treatment can be applied to a material particularly after completion of the container fabrication, to achieve a satisfactory decontamination performance.

A definitive finish for a material to achieve the surface contamination requirement specified by the WPS cannot be given. However, it has been recommended by [41] that decontamination tests are carried out in accordance with BS4247-1 [55], to ensure that the selected material, following any additional surface finish processes, is fit for purpose in terms of its decontamination performance. The decontamination tests should be carried out on the selected material surface finish with the type of contamination likely to be encountered, in order to demonstrate that the non-fixed surface contamination is below the required level.

4.3.6 Gas generation and release

The generation of bulk, radioactive and toxic gases by the waste package shall comply with the requirements for safe transport and disposal.

The release of radionuclides in gaseous form from the waste package shall comply with the assumptions that underpin the safety cases for transport and the GDF operational period.

Gases generated by waste packages transported as part of a Type B transport package shall not:

- **cause the internal pressure of the transport package to exceed a gauge pressure of 700kPa under normal conditions of transport; or**
- **result in the release of radionuclides, in gaseous or particulate form, from the transport package under normal conditions of transport exceeding $10^{-6}A_2$ per hour.**

The release of activity, in gaseous or particulate form, from the waste package during the GDF operational period should not exceed:

- **8kBq/hour per cubic metre of conditioned waste for tritium;**
- **180Bq/hour per cubic metre of conditioned waste for carbon-14; or**
- **150Bq/hour per cubic metre of conditioned waste for radon-222.**

Many of the wastes in the UK ILW inventory have the potential to generate gases by a number of different mechanisms (see below), and at different times during their long-term

management. Gas generation by waste packages can have consequences for their transport and for the GDF operational and post-closure periods.

The physical, chemical, biological and radiological properties of the wastes covered by the Generic Specification for LHW are such that the potential exists for the generation of a wide range of gases [56]. These include:

- the corrosion of metals to produce hydrogen and the release carbon-14 in gaseous form;
- microbial degradation of organic materials, including the prior hydrolysis of cellulose to smaller organic compounds;
- the radiolysis of water, both groundwater and that entrained in the wastefrom, and to a lesser extent, some organic materials;
- the release of tritium and noble gases by diffusion from metals;
- radioactive decay of radium, leading to the generation and release of radon-222; and
- the release of gases labelled with tritium and/or carbon-14 from irradiated graphite.

These different processes tend to occur over significant different timescales and this needs to be considered when the consequences of gas generation by waste packages are being considered. For example, processes requiring water (e.g. corrosion, radiolysis) tend to be relatively short-lived and will cease when the available water is consumed whereas the generation of radioactive gases by long-lived radionuclides can persist for many millennia.

The most significant 'bulk' gases generated by ILW are H₂, CO₂ and CH₄, each of which can be generated by a number of different processes. Any of these gases may include the radionuclides tritium and/or carbon-14 and they can also entrain other radioactive gases such as radioisotopes of argon, krypton and radon which may be present in, or be generated by, waste.

Gases give rise to a range of potential effects that may have an influence on all periods of the long-term management of waste packages. These include:

- excessive pressurisation of sealed transport containers;
- pressurisation, distortion and/or damage to sealed waste containers;
- pressurisation and damage to the wastefrom leading to the production of activity in particulate form;
- releases of radioactive/toxic/flammable gases from waste packages;
- pressurisation and damage to the GDF backfill and host rocks leading to:
 - generation of additional groundwater flow pathways and modification of flow patterns;
 - modification to the rate of re-saturation of disposal vaults; or
 - mineralogical changes leading to changes to the chemical characteristics of the backfill material.

Transport

(i) Bulk gas generation

The IAEA Transport Regulations place restrictions on the generation of gas by the contents of Type B transport packages by way of a requirement to specify a maximum normal

operating pressure²¹ (MNOP) for the cavity of a transport container (Paragraph 664), and by limiting the loss of the radioactive contents (which will include both radioactive gases and activity in particulate form which may be entrained in non-radioactive gases) under normal conditions of transport (NCT) to $10^{-6}A_2$ per hour (Paragraph 659).

The definition of a MNOP for transport packages provides a basis for setting limits for the generation of 'bulk gas' (i.e. all gases irrespective of their chemical or radiological properties) by waste packages during that period. Such a limit for the contents of a nominally sealed transport container, such as a SWTC can be calculated using the MNOP, the 'free volume' of the sealed container (i.e. the volume of the cavity not occupied by the waste or waste package); the time between sealing and receipt at a GDF; and the range of temperatures experienced by the transport package during the transport operation.

Table 6 lists the allowable gas generation rates for each of the current designs of unshielded waste packages when carried in a SWTC-285, assuming that the transport container remains sealed for a period of not more than 28 days, and a MNOP of 800kPa.

Table 6 Bulk gas generation limits for the transport of unshielded waste packages

Waste package type	Maximum gas generation rate (litres/day)
500 litre drum ¹	76
3 cubic metre box (side lifting variant)	134
3 cubic metre box (corner lifting variant)	66
3 cubic metre drum	266
MBGWS box ²	84

Notes: ¹ Per waste package, assuming four identical packages in a transport container

² Carried in a SWTC-150

(ii) Radioactive gases

The $10^{-6}A_2$ per hour limit for the release of activity from a transport package under NCT can be used to derive a limit for the allowable release of gaseous activity from waste packages transported within a transport container. Such gases are assumed to accumulate in the transport container cavity and be gradually released, along with other gases, at a rate determined by the leak rate from the transport container lid seal. A description of the methodology used to determine the permissible gaseous activity release from waste packages can be found in [57]. Table 7 lists the waste package release rates for tritium and all other radioactive gases, the generation limits for a range of radioactive gases can be found in the relevant Contents Specifications (i.e. [57,58, 59, 60]).

²¹ Paragraph 661 requires that the MNOP for a Type B transport package shall not exceed 800kPa absolute pressure, but the actual value has to be defined and justified for each design of transport package.

Table 7 Radioactive gas generation limits for the transport of unshielded waste packages

Waste package type	Maximum gas generation rate (A ₂ /day)	
	Tritium	All other gases
500 litre drum ¹	1.1E-04	4.4E-04
3 cubic metre box (side lifting variant)	1.9E-04	7.6E-04
3 cubic metre box (corner lifting variant)	9.0E-05	3.8E-04
3 cubic metre drum	3.7E-04	1.5E-03
MBGWS box ²	1.2E-04	4.9E-04

Notes: ¹ Per waste package, assuming four identical packages in a transport container

² Carried in a SWTC-150

In the particular case of radon-222, control of the quantity of this gaseous decay product generated by a waste package is primarily by control of the quantity of its parent, radium-226. A consideration of the issues arising from the packaging of radium bearing wastes has resulted in the definition of a methodology for the derivation of limiting waste package inventories for radium-226, above which appropriate measures will need to be taken to limit the release of the gas from the wasteform [61].

(iii) Flammable gases

It is good practice to ensure that flammable mixtures of gases do not occur within enclosed volumes, the most obvious of which is the cavity of a sealed transport container. The flammable gases expected to be produced in the greatest quantity by ILW are hydrogen and methane, both of which have the potential to create explosive mixtures when mixed with air.

For the purposes of defining limits for the generation of such gases in order to eliminate the possibility of the creation of explosive mixtures within the cavity of a transport container the aim should be to limit the concentration of any flammable gas to no more than 75% of its lower flammability limit. Table 8 lists the limits for the generation of hydrogen and methane by each of the current designs of unshielded waste packages when carried in a SWTC-285, assuming that the transport container remains sealed for a period of not more than 28 days. The generation rates of other flammable gases can be found in the Contents Specifications for the relevant transport packages (i.e. [57, 58, 59, 60]).

Table 8 Flammable gas generation limits for the transport of unshielded waste packages

Waste package type	Maximum gas generation rate (litre/day)	
	Hydrogen	Methane
500 litre drum ¹	0.4	0.6
3 cubic metre box (side lifting variant)	0.7	1.0
3 cubic metre box (corner lifting variant)	0.3	0.5
3 cubic metre drum	1.4	2.0
MBGWS box ²	0.4	0.6

Notes: ¹ Per waste package, assuming four identical packages in a transport container

² Carried in a SWTC-150.

It should be noted that the limits specified in Table 8 are significantly more constraining than those defined for bulk gas in Table 6. Accordingly the purging of transport containers with an inert gas (e.g. nitrogen) prior to transport will be required if they are to carry waste packages generating hydrogen or methane at rates greater than those given in Table 8.

(iv) Chemo-toxic gases

The generation of chemo-toxic gases by unshielded waste packages could present a hazard to GDF workers, particularly following the opening of a transport package, when the gases could be released into the GDF atmosphere [62]. A similar methodology as that used for flammable gases is used to set limits for In this case the limits on the basis of ensuring that the concentrations of such gases in areas where transport packages are stored prior to opening do not exceed the Threshold Limit Value (TLV)²² [63]. The generation limits for a range of toxic gases for the different designs of unshielded waste package when carried in a SWTC-285 can be found in the relevant Contents Specifications (i.e. [57, 58, 59, 60]). Many of these 'limits' exceed those for bulk gas generation (Table 6) and are therefore covered by that requirement.

Table 9 lists limits for each of the current designs of unshielded waste packages when carried in a SWTC-285, assuming that the transport container remains sealed for a period of not more than 28 days, for two groups of toxic gases (each with the same TLV) for which the limits are less than those for bulk gas generation:

- Group 1: Arsenic trihydride (Arsine), Hydrogen selenide, Nickel carbonyl
- Group 2: Ozone, Phosphorus oxychloride, Antimony trihydride (Stibine)

²² The TLV is the airborne concentration that workers can be repeatedly exposed to on a daily basis without adverse effect.

Table 9 Toxic gas generation limits for unshielded waste packages

Waste package type	Maximum gas generation rate (litre/day)	
	Group 1	Group 2
500 litre drum ¹	27	49
3 cubic metre box (side lifting variant)	49	96
3 cubic metre box (corner lifting variant)	24	46
3 cubic metre drum	85	162
MBGWS box ²	26	50

Notes: ¹ Per waste package, assuming four identical packages in a transport container

² Carried in a SWTC-150

GDF operational and post-closure periods

During the GDF operational period the ventilation system will be specified such as to prevent unsafe accumulations of toxic, asphyxiating, radioactive, flammable or explosive gases within the disposal vaults and associated facilities, by managing them to safe concentrations and discharging them to the atmosphere.

The release of activity in gaseous form from waste packages has the potential to cause on- and off-site dose during both the GDF operational and post-closure periods. The ESC [20] identifies tritium, carbon-14 and radon-222 as the three most significant radionuclides that could be released from waste packages in gaseous form and that could lead to off-site dose. The generic Operational Environmental Safety Assessment [64] uses a value of 0.01mSv/year (derived from the 2009 Statutory Guidance to the Environment Agency [65]) as a target for the maximum dose to the most exposed group of members of the public due to routine discharges from a GDF. This value is used to define screening levels for the release of gaseous radionuclides from waste packages on the basis that if these levels were exceeded by the entire ILW inventory (i.e. ~360,000m³) the 0.01mSv/year target would be exceeded. Table 10 lists screening levels for the release of activity in gaseous form during the GDF operational period.

Table 10 Radioactive gas release screening levels for unshielded waste packages during the GDF operational period

Waste package type	Activity release rate (Bq/hour)		
	Tritium	Carbon-14	Radon-222
500 litre drum	4,000	90	75
3 cubic metre box	24,000	500	450
3 cubic metre drum	20,000	450	370
MBGWS box	35,000	800	700

In the post-closure period the migration of gases from the disposal vaults is one of the main potential pathways by which radionuclides, and other hazardous materials, might be released to the accessible environment. Gases produced by waste packages in this period could thus have a significant effect on post-closure safety, if the potential for their generation is not managed appropriately at the packaging stage.

Guidance on the amelioration of the effects of gas generation by waste packages

A number of generic approaches can be adopted to reduce the consequences of gas generation by the contents of waste packages:

- The incorporation of an engineered vent²³ into the waste container (provided that this does not cause worker dose to exceed regulatory limits during the operational period);
- The use of a gas permeable waste container material (e.g. concrete);
- The use of a sufficiently robust sealed waste container to contain gases and resist the forces produced by the anticipated maximum internal pressure²⁴; or
- The creation of a chemically inert wasteform to significantly reduce or eliminate the potential for gas generation. This could involve:
 - the drying of waste to remove water, the major component of many gas generation reactions;
 - the mixing of the waste with a suitable encapsulant such as a polymeric material; or
 - the use of a high temperature process (e.g. vitrification) to produce a relatively inert wasteform.

Venting of waste packages to manage the possible consequences of gas generation is the approach recommended by the IAEA guidance on the requirements for waste containers containing ILW [66]. However the presence of a vent leads to the possibility of the release of activity in gaseous and/or particulate form and could be viewed as possibly conflicting with the requirement to ensure adequate containment by the waste container (Section 4.1.5). This leads to the requirement for the vent to be filtered, which could for example be achieved by the use of a proprietary HEPA or sintered filter as part of the vent, or by using a lidding arrangement that incorporates a device such as a labyrinth seal.

The requirement for venting does, however, potentially conflict with a requirement to minimise ingress of water into waste packages in the post-closure period of a GDF. This requirement should be taken into account in vent and filter design and the effective area of the vent minimised.

Precautions should be taken in the waste container design to ensure that there is no alternative gas pathway that could bypass the filtering feature (e.g. through an ineffective body/lid seal), particularly during the earlier, more reactive phases of wasteform evolution.

The following are guidelines on the need for the venting of waste packages and the general requirements of such a system, if it needs to be included in a waste package design:

²³ If such a device is used, its effectiveness over the long term (i.e. up to the time of disposal vault backfilling) will need to be assured.

²⁴ Waste packages manufactured using such waste containers are beyond the scope of this document and will be the subject of future guidance.

- Waste packages should be vented if gas production by the wasteform, over the period during which the waste package will need to be handled, is considered capable of causing pressurisation of the waste container.
- Un-vented waste packages should be sufficiently leak-tight such that they are capable of satisfying the requirements for retention of activity under normal handling conditions or under specified impact and fire accident conditions (Section 4.3.8).
- The design of a venting (and filtration) system should not compromise the ability of the waste package to satisfy the requirements for retention of activity under normal handling conditions or under specified impact and fire accident conditions (Section 4.3.8).
- When considering designs of venting systems, waste packagers should take into account the long-term integrity requirements for the waste package (Section 4.1.5). This should include the longevity of the filter medium under the anticipated conditions of waste package storage.
- The cross-sectional area of the vent should be as small as possible while still satisfying the required performance criteria.
- The use of a 'cap' of inactive grout placed on top of the active wasteform will significantly reduce the activity associated with particulates released from the upper surface of the wasteform.
- The sealing of waste packages with a filtered vent should be sufficiently leak-tight to ensure that the filter performance is not compromised by alternative gas pathways (e.g. through an ineffective body/lid seal), particularly during the earlier, more reactive phases of wasteform evolution.
- The filter should be able to cope with the maximum gas production rate anticipated under normal conditions.
- The dust-holding capacity of the filter should be such that it would be capable of operating with optimum performance over the envisaged storage period and with the potential levels of particulates.
- The filter should be able to satisfy the required performance criteria at temperatures up to 80°C.

4.3.7 Criticality safety

The presence of fissile material, neutron moderators and reflectors in the waste package shall be controlled to ensure that:

- *criticality during transport is prevented;*
- *the risk of criticality during the GDF operational period is tolerable and as low as reasonably practicable; and*
- *in the GDF post-closure period both the likelihood and the consequences of a criticality are low.*

The total quantity of fissile material in the waste package should not exceed 47g.

The quantities of fissile material, neutron moderators and reflectors in the waste package shall be controlled to ensure that the transport package satisfies the criticality safety requirements of the IAEA Transport Regulations.

The UK ILW inventory includes a large number of waste streams which contain significant quantities of fissile material²⁵, mainly in the form discrete pieces of irradiated uranium fuel and surface contamination by fuel bearing dust. The quantities of such materials in waste packages must be limited to ensure that they do not represent an unacceptable criticality safety hazard during transport or following disposal at a GDF.

RWM's approach to achieving the three distinct aspects of criticality safety defined by the GWPS is based on the production of waste packages, which are passively safe in this respect. This is generally achieved by controlling the quantities of fissile material and of neutron moderating and reflecting materials²⁶ within waste packages such that criticality cannot occur under all credible conditions during each period. This approach generally involves determining the limiting quantities of fissile materials that will satisfy each of the three requirements stated above and using the most bounding value as the safe fissile mass (SFM) for the proposed waste packages. Additionally, during waste package manufacture suitable controls will need to be put in place to ensure that the SFM is not exceeded.

The different conditions experienced by waste packages during the three distinct periods of their long-term management (i.e. transport and the GDF operational and post-closure periods) has led RWM to carry out extensive work to develop fissile materials limits for waste packages. This has included, in cooperation with waste producers and industry regulators, the development of methodologies for ensuring criticality safety without placing over onerous demands on the packaging of waste.

RWM has produced extensive guidance on the manner in which adequate criticality safety can be achieved for waste packages containing ILW [67], the ensuing sections summarise that guidance.

Transport

The IAEA Transport Regulations lay down a series of controls that are to be placed on '(transport) packages containing fissile material'. These controls, which are defined in Paragraphs 673 to 686, are generally addressed by way of the Package Design Safety Report (PDSR) which is required to be produced as part of an application for the competent authority approval of every transport package type. The PDSR will contain the results of a detailed analysis of a range of criticality scenarios for the anticipated contents of the

²⁵ 'Fissile material' is generally defined as any material containing uranium-233, uranium-235, plutonium-239 and/or plutonium-241.

²⁶ The three most significant materials of interest are graphite, compounds containing deuterium (hydrogen-2) and beryllium.

transport package and will define limits for the range of fissile radionuclides present in the waste to be transported, along with bounding quantities for other materials related to criticality safety (i.e. neutron moderators and reflectors).

The wide range of wastes in the UK ILW inventory which contain fissile material requires that the PDSR for the anticipated transport packages covers as large a proportion of these wastes as possible. To permit this RWM has developed an approach which includes the definition of a limited number of broad categories of waste, defined on the basis of the general nature of the fissile material they contain. The underlying aim of this approach is to ensure that criticality safety is maintained during transport without the imposition of overly conservative limits on the quantities of fissile material that can be present in waste packages. Three such categories have been defined, on the basis of the 'enrichment'²⁷ of the fissile material a waste contains, and in such a manner as to cover the full range of waste in the ILW inventory:

- Natural/Slightly Enriched Fissile Material: Enrichment $\leq 0.81\%$
- Low Enriched Fissile Material: Enrichment $\leq 5\%$
- General Fissile Material: No enrichment limit

When these categories are applied to waste packages manufactured from the range of standardised unshielded waste containers, a list of limits are generated for each which comprise of a lowest and highest value for each category of fissile material type depending on whether they predominantly contain plutonium or uranium-235.

GDF operational period

All waste packages will need to be shown to be capable of satisfying the GWPS requirements for criticality safety during the GDF operational period. In this context the RWM *Radiological Protection Policy Manual* (RPPM) [68] applies the Health and Safety Executive's (HSE) *Safety Assessment Principles for Nuclear Facilities* (SAPs) [69] to the treatment of Design Basis Accidents (DBAs), which would include criticality incidents. The SAPs requirement ECV.2 states that any containment design (such as that provided by a waste package) should:

'.....incorporate measures to minimise the likelihood of unplanned criticality wherever significant amount of fissile materials may be present.'

This includes a requirement to demonstrate that the risk of criticality during the GDF operational period is ALARP.

Following their receipt at the GDF unshielded waste packages will be transferred underground, removed from their transport configuration where necessary, and emplaced in stacks in the disposal vaults. The height of the stacks will depend on the design of the waste package but it is currently assumed to be up to seven-high for most of the existing designs of unshielded waste package (see Section 4.1.3). From a criticality safety viewpoint the waste packages would be in 'arrays' and neutron interaction between waste packages will have to be considered. It is also assumed that during this period the waste packages will remain passively safe as no significant deterioration of the form of their contents will have occurred. Also the movement of waste packages following receipt at the GDF means that the possibility and consequences of impact accidents for criticality safety has to be taken into account. The criticality safety requirements during the GDF operational period are very similar to those which apply to waste packages during operations at the site of arising, in particular during handling in an interim surface storage facility, so similar considerations will apply. Adequate criticality safety will be achieved by setting limits on the contents of waste packages so that they can be shown to be safe under both normal and a range of credible accident scenarios.

²⁷ In this case 'enrichment' is defined as (uranium-233 + uranium-235 + total plutonium)/(Total uranium + total plutonium).

GDF post-closure period

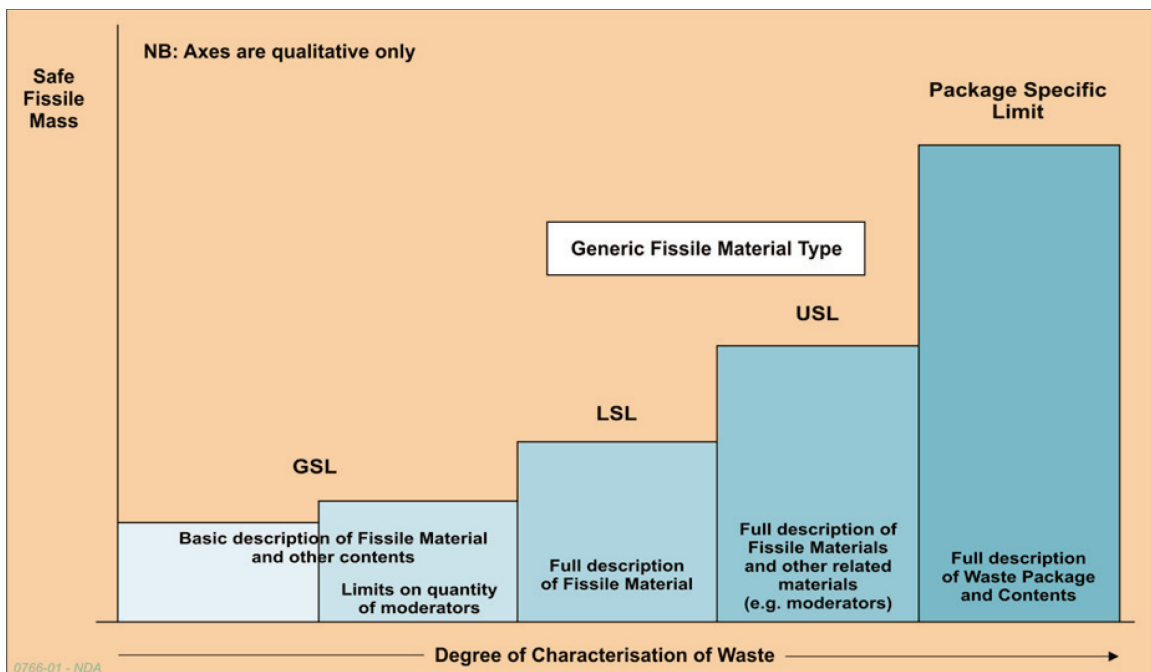
Following the closure of a GDF, waste packages will retain their passive safety for as long as there is no significant deterioration of the containment provided by the waste container and wasteform. In the longer term, following the loss of integrity of those barriers, the potential for the redistribution and accumulation of fissile material will be influenced by the evolution of the GDF system as a whole and, with this in mind, the disposal system is designed to restrict the movement of fissile material. Four classes of post-closure criticality scenario have therefore been considered:

- (i) During the period following backfilling before any significant evolution of the waste package or its contents has occurred;
- (ii) *Package-scale scenarios*, in which evolution of the waste package contents has occurred such that the redistribution of the fissile material can occur within an effectively intact waste container;
- (iii) *Stack-scale scenarios*, in which there is localised degradation (on the scale of a stack of waste packages) and the failure of the waste container such that the accumulation of the fissile material from a limited number of waste packages can occur; and
- (iv) *Vault-scale scenarios*, in which waste package failures are such that the accumulation of the fissile material from a larger number of waste packages can occur.

Method for the determination of SFMs for waste packages

In order to permit an approach to the definition of SFMs that are both proportionate to the risk of criticality and ALARP, RWM has developed a hierarchy of fissile material limits for waste packages that apply the requirements for criticality safety during transport and the GDF operational and post-closure periods. The hierarchy is illustrated in Figure 22 and explained below.

Figure 22 Hierarchy of fissile material limits for waste packages



In recognition of the fact that much of the ILW in the UK inventory contains only small quantities of fissile material RWM has defined a series of 'screening levels' for the fissile material content of waste packages. The lowest of these, the 'General Screening Level' (GSL) aimed at providing a SFM for any unshielded waste package manufactured using a

standardised design of waste container, and which is largely insensitive to the waste type and degree of characterisation of the waste. Earlier work by Nirex [70] concluded that the neutron reactivity of the contents of any waste package containing less than 50gPu239eq. would be so low that criticality safety is ensured under all circumstances during the GDF operational and post-closure periods. More recent work [71, 72] confirmed the validity of this value for the GSL, by showing that all existing designs of unshielded waste package would possess adequate criticality safety provided that they contained no more than 65g of fissile material (i.e. Pu239eq.) if the following additional constraints are met:

- no more than 1kg graphite, 100g beryllium or 100g deuterated material;
- only trace quantities of fissile materials other than uranium-233, uranium-235, plutonium-239 and plutonium-241, or their precursors²⁸; and
- the waste stream does not contain materials that are more efficient neutron moderators than full-density polyethylene homogeneously distributed throughout the waste.

As well as confirming the conservative nature of the 50g value for the GSL the more recent work also added that with 'unlimited' quantities of graphite in a waste package the value would only be reduced to 47g.

Whilst the GSL applies to the GDF operational and post-closure periods only, work has also shown that the most restrictive fissile material limit for the most reactive of the three categories of fissile material considered during transport criticality safety studies (i.e. General Fissile Material, see above), and with no limits on the presence of neutron moderators, was 50g for 500 litre drum waste packages [73] and 97g for 3 cubic metre box or drum waste packages [74].

For waste packages containing quantities of fissile material larger than the GSL RWM has developed a methodology for the determination of safe fissile masses for a range of generic fissile materials types when packaged using standardised designs of waste container. By way of an approach that considers both conservative and more credible criticality scenarios this has resulted in the definition of two screening levels for certain types of fissile material, the basis for their derivation being:

- Lower Screening Level (LSL): Determined by making pessimistic assumptions about wastefrom properties and behaviour in terms of neutronic reactivity. The main assumption made is that fissile material in a waste package is separated from any diluents or neutron poisons (e.g. neutron absorbers such as uranium-238) and intimately mixed with an optimum amount of either water or polyethylene moderator.
- Upper Screening Level (USL): In which some pessimisms made in the determination of the LSL are relaxed and more credible and realistic assumptions are made about the wastefrom. For the USL, it is assumed that the fissile material is well mixed throughout the internal volume of the waste package and that the resulting mixture will be over-moderated²⁹.

²⁸ This requirement will be satisfied for most waste streams that arise from normal operations associated with the nuclear fuel cycle (e.g. fuel fabrication, irradiation in thermal or fast reactors, reprocessing, and decommissioning).

²⁹ Moderators affect the balance between neutron production and neutron losses by slowing neutrons down through scattering events. At lower energy neutrons have a higher chance of causing fission and the presence of moderator can greatly reduce safe limits. However moderators also tend to absorb neutrons and beyond some optimum concentration, the addition of more moderator will reduce reactivity by increasing neutron losses. These systems are said to be 'over-moderated'.

The methodology has been applied to unshielded waste packages manufactured using most³⁰ of the existing standardised designs of waste container and containing defined types of fissile material. Four 'generic fissile materials types' have been defined in a manner that ensures that most of waste streams in the UK inventory of ILW will be covered, these are:

- Low enriched uranium (LEU), with a uranium-235 enrichment of between 0.72% and 5% [75];
- Highly enriched uranium (HEU), with a uranium-235 enrichment of greater than 5% [76];
- Separated plutonium, in which the presence of uranium-238 does not play a significant role [77]; and
- Irradiated natural uranium (INU), with an initial uranium-235 enrichment of up to 0.92% and containing significant quantities of plutonium [78].

The application of the screening level methodology in this way is intended to provide less restrictive screening levels than the GSL and reduce the need for waste packagers to carry out individual criticality safety assessments (CSAs) for every waste stream containing a significant quantity of fissile material.

The final tier of the hierarchy can be used, where required, for waste which are outwith of the descriptions of the four generic fissile material types and/or for which a high degree of characterisation exists. An example would be INU for which it can be demonstrated that no irradiated uranium with an initial enrichment of greater than 0.71% is present. In such cases a 'package specific' CSA, carried out using a complete description of the waste package and its contents³¹, may be able to justify higher fissile material limits (normally in the form of a USL) than those determined for any of the generic fissile materials types. This would sometimes involve the relaxation of some of the conservatism included in the definition of the screening levels for the generic fissile materials types and would require a higher degree of characterisation of the waste, notably regarding the nature of the fissile material and of other materials of significance to criticality safety.

In summary, the hierarchy illustrated in Figure 22 indicates how the limits that will be defined for the fissile material contents of waste package can be increased in response to increasing the degree of characterisation of a waste, and a better definition of waste package design. To permit the definition of a waste package SFM that satisfies all of the requirements for criticality safety whilst being proportional to the risk of criticality that a waste constitutes it is important to consider how each step in the hierarchy is applied.

1. For waste streams containing very small quantities of fissile material, such that would lead to waste packages containing significantly less than the GSL during packaging, this value (i.e. 47g Pu239eq.) can be used without additional restraints, particularly with regard the presence of significant quantities of neutron moderators and reflectors in the waste package.
2. For waste streams where the maximum waste package fissile material content approaches the GSL this value can be used after confirmation that the quantities of other relevant materials (e.g. graphite, beryllium and deuterium) within the waste package will be less than those assumed in its derivation.
3. For waste streams where the maximum waste package fissile material content exceeds the GSL, if the characteristics of the waste are compliant with those underpinning the definition of the relevant LSL, this value can be used.

³⁰ The MBGWS box being the exception.

³¹ This would include a full characterisation of the waste including the nature and quantities of fissile materials and of any other materials of significance to criticality safety.

4. For waste streams where the maximum fissile content exceeds the relevant LSL, the USL can be used if the waste is sufficiently characterised to permit compliance with the underpinning requirements.
5. For all other waste streams a package specific CSA will be required to determine a SFM for the actual characteristics of the waste package and its contents.

In the event that a CSA cannot be used to make a case for the adequate criticality safety of a proposed waste package design, a change to the packaging concept may be required (e.g. to reduce the maximum fissile material content that could occur during waste package manufacture).

Compliance with criticality safety requirements

During the development of proposals to package wastes containing fissile materials, waste packagers will need to take into account all of the aspects of criticality safety discussed above by defining a SFM for the proposed waste packages. The value of SFM will be such as to ensure that the manufactured waste packages will be capable of demonstrating compliance with both the regulatory requirements for their transport and the safety cases for disposal, as defined by the packaging specifications.

By way of example, Table 11 lists the fissile material limits for 500 litre drum waste packages containing a waste in which the fissile material accords with the descriptions of 'low enriched fissile material' (for transport) and LEU (for GDF the operational and post-closure periods).

Table 11 Fissile material limits for 500 litre drum waste packages containing LEU

Period on management	Definition of fissile material content	Screening level	Limit (g)
Transport (Low enriched fissile material)	$2 \times \text{U233} + 1.06 \times \text{U235} + 2 \times (\text{Pu239} + \text{Pu241})$	Lowest ¹	300
	$2 \times \text{U233} + 1.14 \times \text{U235} + 2 \times (\text{Pu239} + \text{Pu241})$	Highest ²	520
GDF operational period	U + Pu	LSL	10,000
	U + Pu	USL	50,000
GDF post-closure period - package scale	U + Pu	LSL	8,100
	U + Pu	USL	65,000
GDF post-closure period - stack-scale	Pu-239	LSL	4,350
	U + Pu	USL	9,300 ³

Notes: ¹ Assuming up to 100g D₂O, 1kg beryllium and 10kg graphite

² Assuming up to 100g D₂O, no beryllium or graphite

³ This being the limit derived from the most restrictive of the stack scale scenarios

On the basis that a waste contains no more than trace quantities of graphite, deuterium or beryllium, and that the nature of the waste and the wasteform is such that the USLs apply, the SFMs for a 500 litre drum waste packages containing LEU would be:

For transport: $2 \times \text{U-233} + 1.14 \times \text{U-235} + 2 \times (\text{Pu-239} + \text{Pu-241}) \leq 520\text{g}$

For GDF operations and post-closure: $\text{U} + \text{Pu} \leq 9,300\text{g}$

It should be noted that no screening levels are listed for the post-closure vault-scale scenarios as these have not been determined by the CSAs. In general such scenarios require the accumulation of the fissile material from a large number of waste packages (i.e. that from a few tens of packages containing the relevant USL and from many hundreds of packages containing the LSL). Accordingly these scenarios will not generally be used in the definition of SFMs for individual waste packages but will be considered as part of the disposability assessment of the proposals to package a waste stream as a whole.

The waste packager will also be required to show that steps will be taken during the actual packaging of the waste to ensure that the SFM cannot be exceeded under all credible circumstances. To this end, as part of a submission for the disposability assessment of proposed waste packages, waste packagers will be required to produce *Criticality Compliance Assurance Documentation* (CCAD). The CCAD will consider the quantity and form of the fissile materials in a waste stream and define the procedural controls will be put in place to ensure that a defined SFM will not exceeded during waste package manufacture. RWM has produced guidance on the preferred format of CCAD, and the means by which such documentation can be produced [79].

4.3.8 Accident performance

Under all credible accident scenarios the release of radionuclides and other hazardous materials from the waste package shall be low and predictable.

The waste package should exhibit progressive release behaviour within the range of all credible accident scenarios.

The impact and fire accident performance of the waste package shall comply with the assumptions that underpin the safety cases for transport and the GDF operational period.

The accident performance of the waste package shall ensure that, in the event of any credible accident during the GDF operational period, the on- and off-site doses resulting from the release of radionuclides from the waste package shall be as low as reasonably practicable and should be consistent with meeting the relevant Basic Safety Levels.

Waste packages may be subject to a range of accident conditions during their long-term management, up until the end of the GDF operational period. Specifically these include minor impacts during normal handling and more severe accidents involving impacts and/or fires during transport and the GDF operational period. All such accidents are a potential mechanism for the release of radionuclides from waste packages into the environment in an uncontrolled manner and/or the exposure of workers and members of the public to radiation.

The safety cases for transport and the GDF operational period consider the consequences of such accidents, which may involve impact and/or fires, and make assumptions regarding the performance of waste packages under such conditions. Waste packages must therefore be capable of being compliant with assumptions regarding their performance in response to specified impact and fire challenges, a matter that is assessed during the disposability assessment of a packaging proposal. Additionally all waste packages must be capable of limiting the release of radionuclides following such challenges such that radiation doses to workers and members of the public are ALARP and less than the relevant regulatory limits.

RWM has produced extensive guidance on the manner by which the accident performance of waste packages containing LHW is treated [80], the ensuing sections summarise that guidance.

Transport

The ability of transport packages to withstand the effects of accidents is an important aspect of the IAEA Transport Regulations and the requirements they define are applied indirectly to unshielded waste packages which are generally transported within a protective transport container as Type B transport packages. The impact and fire challenges for such transport packages are defined in Paragraphs 726 to 729 (*'Tests for demonstrating the ability to withstand accident conditions of transport'*). Specifically this requires that Type B transport packages be subjected to the cumulative effects of defined mechanical and thermal challenges (these being defined as an analogue of a transport accident comprising an impact followed by a fire) following which the accumulated loss of activity from the transport package in a period of one week must not exceed $1A_2$ ³².

The TSC [43] is founded on the assumption that all transport packages will be capable of complying with the requirements for their performance under specified 'accident conditions of transport' (ACT), as defined by the IAEA Transport Regulations.

For Type B transport packages ACT comprises a mechanical test and a thermal test:

The mechanical test (Paragraph 727) comprises:

- a) A drop of the transport package from a height of 9m on to a flat horizontal surface;
- b) A drop of the transport package from a height of 1m on to a specified aggressive feature; and
- c) The drop of a 500kg mass from a height of 9m on to the transport package.

The thermal test (Paragraph 728) comprises:

- a) The exposure of the transport package for 30 minutes to a fully engulfing fire with an average flame temperature of 800°C; and
- b) The exposure of the transport package to specified solar insolation conditions.

Paragraph 659 defines a limit for the accumulated loss of activity from a transport package in a period of one week following exposure to ACT to $1A_2$ (or $10A_2$ of krypton-85).

For unshielded waste packages carried in a SWTC it is assumed that ACT will result in damage to the waste package and the release of activity in particulate and/or gaseous form. This activity could subsequently escape from the transport container through the lid seal which has been 'damaged'³³ as a result of the accident.

The quantity of activity released from a transport package following an accident can be determined from:

$$\text{Fraction of total activity released} = \frac{\text{Waste package release fraction (RF)}}{\text{Transport container decontamination factor (DF)}}$$

Where: RF is defined as the fraction of the total contents of a waste package (in terms of the mass of material or the activity associated with that material) released as a consequence of a defined accident; and

DF is defined as the effective attenuation of the release from a waste package by the transport container.

³² Or not more than $10A_2$ for krypton-85

³³ It should be noted that the degree of damage to the seal is relatively small, such as would lead to an increase of a factor of ~10 over the pre-accident leak rate. It is also assumed that the transport container would be sufficiently robust to prevent activity from escaping by any other route.

The manner by which particulate activity released by a damaged waste package can escape from the transport container is influenced significantly by the behaviour of the particles within the cavity of a transport container. Work has been carried out to investigate the extent to which such particles will adhere to surfaces within the transport container and/or agglomerate to form particles too large to pass through the leaking transport container lid seal [81]. The 'Adhesion and Agglomeration' methodology has been applied to unshielded packages carried in the SWTC and this has indicated that a significant benefit can be claimed for such effects. This is reflected in DF values of over 1000 which, when combined with typical impact RF values for unshielded waste packages [82] results in values of the order of 10^{-8} for the fraction of the total waste package inventory that would be released from a transport package as a result of the impact component of ACT. Such values mean that waste package inventories of the order of $10^7 A_2$ could be carried in an SWTC without the $1A_2$ limit for the release of activity from a transport package being exceeded.

In the case of the fire component of a transport accident a similar approach to that described above for the impact component is adopted. For non-gaseous radionuclides, similar waste package radionuclide inventories (i.e. $\sim 10^7 A_2$) would be necessary to result in a transport package release of $1A_2$, although the restrictions on gaseous radionuclides (and gases labelled with species such as carbon-14) would be much greater. In the case of the latter no benefit could be claimed for agglomeration or adhesion and gaseous activity would be able to escape through the transport container seal if a sufficient pressure difference existed. Table 12 lists waste package inventory limits for gaseous radionuclides, pessimistically calculated assuming the highest internal pressure permitted for a SWTC.

Table 12 Limits on the inventories of gaseous radionuclides set by the fire component of ACT

Waste package type	Activity limit per waste package		
	Tritium (A_2 /TBq)	Krypton-85 (A_2 /TBq)	Other gases (A_2)
500 litre drum	0.88/35.2	28.8/288	2.9
3 cubic metre box - corner lifting variant	0.76/30.4	24.9/249	2.5
3 cubic metre box - side lifting variant	1.55/62.0	50.4/504	5.0
3 cubic metre drum	3.08/123.2	100/1000	10.0
MBGWS box (carried in SWTC-150)	0.97/38.9	31.6/316	3.2

The values given for tritium in Table 12 may prove to be the bounding factor for waste packages containing tritium-rich wastes. However such waste streams make up a very small proportion of the ILW inventory and the manner of their conditioning could incorporate specific measures to reduce the escape of tritium from waste packages under both NCT and ACT [83].

GDF operational period

During the GDF operational period the potential exists for unprotected unshielded waste packages to be exposed to accidents involving impacts and/or fire (or both together) which would result in them being subject to a range of mechanical and thermal challenges. Such

challenges could result in damage to waste packages, the release of radionuclides within the GDF, and radiation dose to both workers on-site and members of the public off-site. An analysis of the consequences of accidents involving waste packages during the GDF operational period forms part of the generic Operational Safety Case (OSC) [84].

RWM has identified a range of accidents that could affect waste packages during the GDF operational period, and that could result in the release of radionuclides and radiation dose to workers on-site and/or members of the public off-site [85]. These accidents include:

- The dropping of waste packages on to floors or equipment within the GDF;
- The dropping of equipment (including other waste packages and transport container lids) on to waste packages;
- The collapse of single or multiple stacks of waste packages;
- Extreme facility mechanical failures, such as impacts with stacker trucks or the collapse of vault roofs on to waste packages; and
- Fires caused by a variety of faults.

As well as requiring that the doses resulting from accidents in which radionuclides are released are ALARP the HSE SAPs define Basic Safety Objectives (BSOs) for the cumulative annual on- and off-site doses due to accidents on nuclear sites. The SAPs also define Basic Safety Levels (BSLs) as targets for the maximum on- and off-site dose that could result from release of radionuclides as a result of individual DBAs, on the basis of the expected frequency of the initiating event that would result in such an accident (Table 13). The highest of these BSLs, for accidents with an expected initiating event frequency of less than 10^{-4} per annum, are therefore used as upper bounds for the dose consequences of GDF accidents. However, for accidents for which a higher fault frequency cannot be discounted, the lower BSLs will apply.

Table 13 Basic Safety Level doses for design basis accidents

DBA fault frequency	BSL for on-site dose	BSL for off-site dose
$>1 \times 10^{-3}$ pa	20mSv	1mSv
Between 1×10^{-3} and 1×10^{-4} pa	200mSv	10mSv
$<1 \times 10^{-4}$ pa	500mSv	100mSv

It should be noted although the BSLs are targets for the maximum on- and off-site dose that would result from DBAs it is HSE policy that new facilities should at least meet the relevant values. This is on the basis that simply meeting the BSL values may not be ALARP for the facility. In practice, the design of a GDF, and the waste packages that will be disposed there, should be such as to ensure that the doses resulting from DBAs are ALARP and meet targets that reflect modern nuclear safety standards and expectations. To this end, our aim is to reduce such doses to those defined in the RPPM [68] as BSOs for the annual on- and off-site doses (i.e. 0.1mSv and 0.01mSv respectively) for accidents involving the release of activity from waste packages occurring at a GDF.

GDF impact accidents

Following their receipt at the GDF, unshielded waste packages would be transferred underground in their transport container from which they will be unloaded, in a shielded cell, and then transferred to the dedicated disposal vaults using remote systems. The waste packages will be stacked up to seven high by the use of an overhead crane. Such a

process has the potential to result in a range of impact accidents that could affect waste packages

All impact accidents are assumed to subject waste packages to the mechanical challenge which would result from a free drop from a height at the location at which the fault occurs, and on to a 'target' with defined properties. Faults may involve the impact of a waste package on to a 'flat unyielding' surface such as the floor of a disposal vault, or on to an 'unyielding aggressive feature' such as the corner of another waste package, or the stacking post of a stillage (Figure 2).

A review of the potential for impact accidents affecting unshielded waste packages during the operational period of the GDF has concluded that the most severe impacts would occur in a GDF constructed in a geology characterised as higher strength rock, and with a maximum vault height of 15m, and would be [86]:

- a drop onto a flat unyielding target from a height of 11m; and
- a drop onto an aggressive feature (such as the corner stacking post of a waste package) from a height of 10m.

Other, more extreme faults have also been identified, including the collapse of a vault roof or a handling crane on to waste packages, or the consequences of a 'runaway' transporter in the drift access to the underground facilities. Such faults could result in more severe impacts than those defined above, and could affect groups of waste packages rather than individuals. However, it is also assumed that sufficient safety features would be incorporated in the design of relevant GDF systems to ensure that such events would occur with an initiating event frequency of less than 10^{-3} pa.

The definition of the size of particles that will contribute to dose following an impact accident has significance in the definition of waste package impact performance. Historically it had been assumed that all particles with sizes of up to $100\mu\text{m}$ would need to be taken into account during the assessment of the consequences of impact accidents in the GDF. It was however acknowledged that this value may be over conservative, especially when the conclusions of an International Commission on Radiological Protection study into the matter are considered [87]. As a means of justifying a reduction in this conservatism RWM has recently commissioned work to determine what constitutes a 'respirable particle' in the context of a GDF [88, 89] and this has led to a reduction to $10\mu\text{m}$ in the maximum size of particles that need to be considered in the analysis of GDF impact accidents.

GDF fire accidents

A range of accidents has been identified that could result in fires during the operational period and that could result in the release of radionuclides from waste packages and the potential to cause radiation dose to both workers on-site and members of the public off-site [85].

Whilst the design of a GDF would be such as to minimise the possibility of faults that could lead to fires, work has been commissioned to determine the potential severity of the fires that could result from such faults. Historically this had led to the conclusion that a DBA fire accident should be defined as a fully engulfing 60 minutes hydrocarbon pool fire with an average flame temperature of 1000°C [90]. These values are significantly more severe than those specified by the IAEA Transport Regulations for transport accidents (i.e. 30 minutes/ 800°C) and this deliberate conservatism was based on a consideration of complicating factors such as restricted access and firefighting capabilities in a GDF, including a review of the outcomes of investigations of a number of fires in similar circumstances [91].

More recent work has shown that the fire duration for unshielded waste packages in a GDF constricted in the most bounding geology can be reduced to 30 minutes [92].

Assessing the consequences of GDF impact and fire accidents

In order to determine the potential consequences of proposed waste packages for the operational safety of a GDF RWM has developed a methodology that allows the radiological consequences of a wide range of accidents involving the waste packages to be determined [93]. The methodology is applied to specific designs of waste package by way of the *Repository Operational Safety Assessment (ROSA)* 'toolkit' [94]. In calculating the dose consequences of accidents, the toolkit considers a number of factors for specific waste package designs including:

- The radionuclide inventory of the proposed waste packages;
- The RFs for the challenges presented by the accidents;
- The availability and efficiency of protective equipment and the ventilation system within a GDF;
- The anticipated proximity, exposure times and breathing rates etc. of on-site workers to radionuclides released during accidents; and
- The exposure routes to members of the public following an off-site release.

For the purposes of guidance, the ROSA toolkit has been used to determine the releases of activity that would lead to the lowest BSLs being equalled for the impact and fire accidents with the greatest on- and off-site dose consequences. These are listed in Table 14 for a range of the most significant radionuclides that are found in the wastes that would typically be packaged in unshielded waste packages.

The values in Table 14 can be used by waste packagers as a means of identifying issues that may exist regarding the impact and/or fire accident performance of proposed unshielded waste packages.

During the evaluation of operational safety that takes place as part of the disposability assessment of proposals to package waste a full evaluation of the dose consequences of impact and fire accidents involving the proposed waste packages is carried out. The inputs to such an evaluation will include the maximum radionuclide inventory derived as part the disposability assessment and representative RF values for the waste package type. The RFs for different designs of unshielded waste packages will depend on both the waste container type and the nature of the wastefrom. A significant amount of RF data is available for the current designs of unshielded waste package, derived from a combination of finite element modelling and small scale and full size testing [95]. Table 15 lists recommended impact RFs for the existing designs of unshielded waste package, standardised for the impact resulting from drops from a height of 10m onto a 'flat unyielding' surface, and for typical wastefroms for each waste package type. Indicative RFs for other drop heights can be determined by simple scaling (i.e. $RF \propto \text{drop height}$).

As noted above, impact accidents can involve waste packages impacting a range of different target types; flat or aggressive, yielding or unyielding, and the magnitude of the RF can depend significantly on the nature of such a target. The consequences of impacts against more aggressive targets such as the corner pillar of another waste package, a stillage or other GDF equipment may also need to be considered in an analysis of the impact accident performance of a proposed waste package design. In this context the RF values given in Table 15 can be used to produce conservative values for the expected releases resulting from the impact of waste packages on to the unyielding floor of a disposal vault. RWM is currently considering the consequences of impacts on to yielding surfaces and representative aggressive features, either of which could result in different RF values.

Table 14 Activity releases from unshielded waste packages resulting in BSL for faults with frequency $>10^{-3}$ pa

Nuclide	Allowable activity release from disposal unit ³⁴ (TBq)			
	Impact Accidents		Fire Accidents	
	Off-Site (1mSv)	On-Site (20mSv)	Off-Site (1mSv)	On-Site (20mSv)
Am-241	3.77E+00	2.47E-04	9.25E+00	2.77E-03
C-14	5.75E+05	1.65E+01	3.62E+00	1.87E+02
Cl-36	1.01E+02	1.40E+00	6.33E-04	1.56E+01
Co-60	5.18E+01	3.32E-01	3.27E+01	3.72E+00
Cs-137	5.65E+02	1.44E+00	3.55E+01	1.61E+01
H-3	1.37E+08	2.35E+02	8.62E+02	2.64E+03
I-129	5.35E+00	1.00E-01	3.37E-05	1.12E+00
Ni-63	1.37E+04	4.81E+00	8.62E+03	5.41E+01
Pu-239	5.65E+00	2.05E-04	3.56E+00	2.30E-03
Pu-240	5.65E+00	2.05E-04	3.56E+00	2.30E-03
Pu-241	3.85E+02	1.13E-02	2.43E+03	1.27E-01
Se-79	5.35E+01	3.11E+00	3.37E-04	3.48+01
Sr-90	1.71E+01	6.41E-02	1.08E+01	7.19E-01
Tc-99	1.01E+02	2.47E+00	6.33E+01	2.77E+01
U-235	2.59E+01	1.25E-03	1.63E+01	1.40E-02
U-238	1.72E+01	1.32E-03	1.09E+01	1.48E-02

³⁴ A 'disposal unit' being a single 3 cubic metre box or drum, a MBGWS box or a stillage containing four 500 litre drums.

Table 15 Recommended impact RFs for unshielded waste packages

Waste package type	Wasteform type	RF for impact resulting from a drop from 10m onto a flat unyielding surface
500 litre drum	Homogeneous waste	1.6E-04
	Heterogeneous waste	3.2E-04
	Annular grouted	8.0E-05
3 cubic metre box	Heterogeneous waste	8.0E-05
3 cubic metre drum	Homogeneous waste	8.0E-05
MBGWS box ³⁵	Heterogeneous waste	8.0E-05

Fire RFs are a function of waste package type (i.e. container and wasteform), fire severity (i.e. temperature and duration) and the volatility of the radionuclides they contain. To simplify the treatment of the latter aspect RWM has grouped all of the elements that could be present in ILW into six 'volatility groups' (0) and define a RF for each group.

Table 16 Volatility groups for ILW

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

Table 17 lists the recommended fire RFs the existing designs of unshielded waste package with a range of typical cemented wasteforms, for each of the volatility groups for a 1000°C/60 minute³⁶ fire.

³⁵ No drop testing or modelling of the MBGWS box waste package has been conducted. For the purposes of disposability assessment the recommended RF value for the 3 cubic metre box waste packages is used.

Table 17 Recommended fire RFs for unshielded waste packages (1000°C/60 minute fire)

Waste package type	Wasteform type	RF for volatility group					
		I	II	III	IV	V	VI
500 litre drum	Homogeneous waste	1	3E-03	4E-03	1E-03	1E-04	1E-04
	Heterogeneous waste	1	9E-04	9E-04	6E-05	3E-05	3E-05
	Annular grouted	1	3E-04	3E-04	2E-05	3E-06	3E-06
3 cubic metre box	Heterogeneous waste	1	1E-03	1E-03	6E-05	3E-05	3E-05
3 cubic metre drum	Homogeneous waste	1	1E-02	1E-03	6E-04	1E-04	1E-04
MBGWS box	Heterogeneous waste	1	7E-04	7E-04	6E-05	3E-05	3E-05

It should be noted that for waste packages containing different types of wasteform significant variations from the RFs listed in Table 17 may occur. For example higher RFs may be necessary for non-encapsulated wasteforms whereas lower RFs may apply to vitrified wasteforms produced by high temperature processes. For wasteforms with significantly different properties to those assumed for the RFs listed above, additional modelling and/or testing may be required in order to derive more representative values.

Designing waste packages for optimum impact and fire accident performance

When designing a waste package for optimum impact performance the main aims are to achieve low and predictable damage (and the associated release of activity) which is progressive with increasing impact severity. Since the impact performance of a waste package is controlled by the properties of both the wasteform and the waste container both components should ideally play effective and independent roles in minimising the release of activity.

The two key mechanical properties of a waste container material, namely brittle fracture and ductility, have been identified as controlling the impact performance of a waste container [65]. Design features of the waste container such as the lid/body connection and container design specifications such as weld locations and type will have the potential to significantly affect impact performance. In general waste container design should avoid stiff, unyielding features juxtaposed to soft yielding features. In such a configuration there is the possibility of waste container rupture by punching and shear strain concentration [65]. Such a scenario can occur when heavy non-deformable objects are encapsulated within a wasteform. Under impact conditions the object may dislodge encapsulation grout

³⁶ As noted above, a duration of 30 minutes is currently assumed for fires affecting unshielded waste packages. No RFs have yet been derived for these conditions and the values given in Table 17 should be used in the interim.

that in turn, may strike the container walls or the lid, or the object itself may strike the container walls or lid.

The fire performance of a waste package is similarly controlled by the properties of both the wasteform and waste container. In this case the waste container forms the primary barrier to an external heating source, protecting the wasteform from direct contact with the fire. It will also restrict the supply of oxygen to the wasteform thereby reducing the possibility of wasteform combustion. The waste container also plays an important role in the overall containment of activity within the waste package during a fire accident. Experimental work with waste packages containing cementitious wasteforms [96] has shown that steam and gases generated within the wasteform provide a major driving force for the escape of activity. The presence of an intact waste container would have a significant effect in reducing such releases.

Modelling and experimental work [96, 97] has shown that higher temperatures, at which the fraction of radionuclides liable to be released from the wasteform may be significant, tends to be restricted to a thin layer around the outside of the wasteform. Accordingly, the thermal properties of the waste container could have a significant effect on the overall performance of the waste package during fire accidents.

The pathway between the waste container and the wasteform is considered to have a significant role in allowing steam and gases generated in the wasteform to be released from the package vent. Failure of such pathways may cause pressurisation of the waste package.

In view of the above, the particular properties of the material used for waste containers which would give benefits during a fire accident would be:

- high melting temperature (i.e. $>1000^{\circ}\text{C}$) – to ensure that overall containment is maintained;
- lack of phase transitions at temperatures below 1000°C – as above;
- non-combustibility – as above;
- low thermal expansion – to limit the possibility of waste container failure due to uneven expansion;
- low thermal conductivity – to limit the conduction of heat to the wasteform.

The role played by the wasteform in achieving the required waste package performance during impact and/or fire accidents is dealt with in detail in the wasteform guidance that complements this document (i.e. [6, 7]).

5 Summary

The Generic Specification for waste packages containing LHGW [3] defines the requirements for all such waste packages, irrespective of the design and nature of the waste container or the wasteform they contain. The DSTS [4] identifies a limited range of standardised designs of waste container which are suitable for the packaging of LHGW in a form suitable for transport to and disposal in a GDF.

This document explains the manner by which the requirements of the Generic Specification are applied to unshielded waste packages and provides guidance on the means by which those requirements could be achieved for actual waste packages.

Whilst this guidance is primarily aimed at waste packages manufactured using the existing standardised designs of waste container, much of the information it contains is relevant to other approaches to the packaging of waste that would result in the manufacture of waste packages that could be described as 'unshielded'. Users are encouraged to contact RWM at an early stage in the development of such approaches.

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Appendix A Constraints placed on Type B transport packages by the IAEA Transport Regulations

Transport package parameter	Limits or constraints on Type B transport packages
Total activity content	<p>Para 630: A limit of $10^5 A_2$ is placed on the contents of such transport packages which have not been qualified to satisfy the requirements of an 'enhanced water immersion test'.</p> <p>No activity limit is placed on transport packages which are so qualified (Para 730).</p>
Non-fixed surface contamination	<p>Para 508: When averaged over any area of 300cm^2, non-fixed surface contamination (of transport package) shall not exceed 4Bqcm^{-2} for beta and gamma emitters and low-toxicity alpha emitters, and 0.4Bqcm^{-2} for other alpha emitters.</p>
External dose rate	<p>Para 570: Under conditions of exclusive use - not more than 10mSvh^{-1} at the surface and 0.1mSvh^{-1} at 2m from the surface.</p> <p>Para 566: Under conditions of non-exclusive use - not more than 2mSvh^{-1} at the surface and 0.1mSvh^{-1} at 1m from the surface.</p>
External surface temperature	<p>Para 654: With an ambient temperature of 38°C and in the absence of solar insolation the surface temperature should not exceed 50°C, unless carried under the terms of exclusive use.</p> <p>Para 655: When carried under the terms of exclusive use, the surface temperature should not exceed 85°C.</p>
Heat generation	<p>Para 565: Additional operational controls may be required for the stowage and storage of transport packages that have an average surface heat flux of greater than 15Wm^{-2}.</p>
Gas generation	<p>The internal pressure of the transport package shall not exceed the MNOP for which it has been designed. A transport package shall not have a MNOP of greater than 700kPa (Para 664).</p>
Release of activity during normal transport operations	<p>Para 659(a): When submitted to specified mechanical challenges (Para's 719 and 724) the release of radioactive contents from the package should not exceed $10^{-6} A_2\text{h}^{-1}$</p>
Release of activity following a transport accident	<p>Para 659(b) (ii): When submitted to specified mechanical and thermal challenges (Para's 726 - 729) the package shall be capable of limiting the release of activity to a total of $1A_2$ in a period of one week.</p>
Control of fissile material	<p>Para 673: Packages must be able to be shown to be capable of remaining subcritical, singly and in arrays, under all normal and credible accident conditions.</p>
Stacking	<p>Para 723: Transport packages should be capable of resisting a compressive load equal to 5 times their maximum weight for a period of 24 hours, following which they must be capable of satisfying the requirements of Para 622 (i.e. to prevent the loss or dispersal of contents or loss of shielding integrity).</p>

Glossary of terms used in this document

activity

The number of atoms of a radioactive substance which decay by nuclear disintegration each second. The SI unit of activity is the becquerel (Bq) equal to one radioactive decay per second.

The IAEA Transport Regulations define a unit of activity, the A_2 , as a means of standardising the dose consequences of different radionuclides on the basis of the different possible exposure pathways that could occur following the release of radionuclides from a transport package. A_2 values (in TBq) for a wide range of radionuclides are listed in Table 2 of the IAEA Transport Regulations [18].

alpha activity

Alpha activity takes the form of particles (helium nuclei) ejected from a decaying (radioactive) atom. Alpha particles cause ionisation in biological tissue which may lead to damage. The particles have a very short range in air (typically about 5cm) and alpha particles present in materials that are outside of the body are prevented from doing biological damage by the superficial dead skin cells, but become significant if inhaled or swallowed.

backfill

A material used to fill voids in a GDF. Three types of backfill are recognised:

- local backfill, which is emplaced to fill the free space between and around waste packages;
- peripheral backfill, which is emplaced in disposal modules between waste and local backfill, and the near-field rock or access ways; and
- mass backfill, which is the bulk material used to backfill the excavated volume apart from the disposal areas.

backfilling

The refilling of the excavated portions of a disposal facility after emplacement of the waste.

barrier

A physical or chemical means of preventing or inhibiting the movement of radionuclides.

beta activity

Beta activity takes the form of particles (electrons) emitted during radioactive decay from the nucleus of an atom. Beta particles cause ionisation in biological tissue which may lead to damage. Most beta particles can pass through the skin and penetrate the body, but a few millimetres of light materials, such as aluminium, will generally shield against them.

buffer

An engineered barrier that protects the waste package and limits the migration of radionuclides following their release from a waste package.

conditioning

Treatment of a radioactive waste material to create, or assist in the creation of, a wasteform that has passive safety

container

The vessel into which a wasteform is placed to form a waste package suitable for handling, transport, storage and disposal.

containment

The engineered barriers, including the waste form and packaging, shall be so designed, and a host geological formation shall so be selected, as to provide containment of the waste during the period when waste produces heat energy in amounts that could adversely affect the containment, and when radioactive decay has not yet significantly reduced the hazard posed by the waste

criticality

A state in which a quantity of fissile material can maintain a self-sustaining neutron chain reaction. Criticality requires that a sufficiently large quantity of fissile material (a critical mass) be assembled into a geometry that can sustain a chain reaction; unless both of these requirements are met, no chain reaction can take place and the system is said to be sub-critical.

criticality safety

A methodology used to define the conditions required to ensure the continued sub-criticality of waste containing fissile material.

disposability

The ability of a waste package to satisfy the defined requirement for disposal.

disposability assessment

The process by which the disposability of proposed waste packages is assessed. The outcome of a disposability assessment may be a Letter of Compliance endorsing the disposability of the proposed waste packages.

disposal

In the context of solid waste, disposal is the emplacement of waste in a suitable facility without intent to retrieve it at a later date; retrieval may be possible but, if intended, the appropriate term is storage.

disposal facility (for solid radioactive waste)

An engineered facility for the disposal of solid radioactive wastes.

disposal system

All the aspects of the waste, the disposal facility and its surroundings that affect the radiological impact.

disposal vault

Underground opening where ILW or LLW waste packages are emplaced.

dose

A measure of the energy deposited by radiation in a target.

dose rate

The effective dose equivalent per unit time. Typical units of effective dose are sievert/hour (Sv h^{-1}), millisieverts/hour (mSv h^{-1}) and sievert/year (Sv y^{-1}).

emplacement (of waste in a disposal facility)

The placement of a waste package in a designated location for disposal, with no intent to reposition or retrieve it subsequently.

Environment Agency (EA)

The environmental regulator for England and Wales. The Agency's role is the enforcement of specified laws and regulations aimed at protecting the environment, in the context of

sustainable development, predominantly by authorising and controlling radioactive discharges and waste disposal to air, water (surface water, groundwater) and land. The Environment Agency also regulates nuclear sites under the Environmental Permitting Regulations and issues consents for non-radioactive discharges.

environmental safety case

The collection of arguments, provided by the developer or operator of a disposal facility, that seeks to demonstrate that the required standard of environmental safety is achieved.

fissile material

Fissile material is that which undergoes fission under neutron irradiation. For regulatory purposes material containing any of the following nuclides is considered to be 'fissile': uranium-233, uranium-235, plutonium-239 and plutonium-241.

gamma activity

An electromagnetic radiation similar in some respects to visible light, but with higher energy. Gamma rays cause ionisations in biological tissue which may lead to damage. Gamma rays are very penetrating and are attenuated only by shields of dense metal or concrete, perhaps some metres thick, depending on their energy. Their emission during radioactive decay is usually accompanied by particle emission (beta or alpha activity).

geological disposal

A long term management option involving the emplacement of radioactive waste in an engineered underground geological disposal facility or repository, where the geology (rock structure) provides a barrier against the escape of radioactivity and there is no intention to retrieve the waste once the facility is closed.

geological disposal facility (GDF)

An engineered underground facility for the disposal of solid radioactive wastes.

half-life

The time taken for the activity of a given amount of a radioactive substance to decay to half of its initial value. Each radionuclide has a unique half-life.

hazardous materials

Materials that can endanger human health if improperly handled. As defined by the Control of Substances Hazardous to Health Regulations, 2002.

Health and Safety Executive (HSE)

The HSE is a statutory body whose role is the enforcement of work-related health and safety law. HSE is formally the licensing authority for nuclear installations in Great Britain, although the licensing function is administered on HSE's behalf by its executive agency the Office for Nuclear Regulation (ONR).

higher activity radioactive waste

Generally used to include the following categories of radioactive waste: low level waste not suitable for near surface disposal, intermediate level waste and high level waste.

immobilisation

A process by which the potential for the migration or dispersion of the radioactivity present in a material is reduced. This is often achieved by converting the material to a monolithic form that confers passive safety to the material.

Industrial Package (Type-IP)

A category of transport package, defined by the IAEA Transport Regulations for the transport of radioactive materials with low specific activities.

intermediate level waste (ILW)

Radioactive wastes exceeding the upper activity boundaries for LLW but which do not need heat to be taken into account in the design of storage or disposal facilities.

International Atomic Energy Agency (IAEA)

The IAEA is the world's centre of cooperation in the nuclear field. It was set up as the world's "Atoms for Peace" organization in 1957 within the United Nations family. The Agency works with its Member States and multiple partners worldwide to promote safe, secure and peaceful nuclear technologies.

Letter of Compliance (LoC)

A document, prepared by RWM, that indicates to a waste packager that a proposed approach to the packaging of waste would result in waste packages that are compliant with the requirements defined by relevant packaging specifications, and the safety assessments for transport to and disposal in a GDF, and are therefore deemed 'disposable'.

low level waste (LLW)

Radioactive waste having a radioactive content not exceeding 4 gigabecquerels per tonne (GBq/t) of alpha or 12 GBq/t of beta/gamma activity.

low specific activity (LSA) material

A material classification defined by the IAEA Transport Regulations as 'Radioactive material which by its nature has a limited specific activity (i.e. activity per unit mass of material), or radioactive material for which limits of estimated average specific activity apply.'

Managing Radioactive Waste Safely (MRWS)

A phrase covering the whole process of public consultation, work by CoRWM, and subsequent actions by Government, to identify and implement the option, or combination of options, for the long term management of the UK's higher activity radioactive waste.

Nirex (United Kingdom Nirex Limited)

An organisation previously owned jointly by Department for the Environment, Food and Rural Affairs and the Department for Trade and Industry. Its objectives were, in support of Government policy, to develop and advise on safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials in the United Kingdom. The Government's response to Committee on Radioactive Waste Management in October 2006 initiated the incorporation of Nirex functions into the NDA, a process which was completed in March 2007.

Nuclear Decommissioning Authority (NDA)

The NDA is the implementing organisation, responsible for planning and delivering the GDF. The NDA was set up on 1 April 2005, under the Energy Act 2004. It is a non-departmental public body with designated responsibility for managing the liabilities at specific sites. These sites are operated under contract by site licensee companies (initially British Nuclear Group Sellafield Limited, Magnox Electric Limited, Springfields Fuels Limited and UK Atomic Energy Authority). The NDA has a statutory requirement under the Energy Act 2004, to publish and consult on its Strategy and Annual Plans, which have to be agreed by the Secretary of State (currently the Secretary of State for Trade and Industry) and Scottish Ministers.

Office for Nuclear Regulation (ONR)

The HSE's executive agency ONR is responsible for regulating the nuclear, radiological and industrial safety of nuclear installations and the transport of radioactive materials in Great Britain under the Nuclear Installations Act 1965 (NIA 65) and the Carriage of Dangerous Good Regulations.

The Government intends to bring forward legislation to establish ONR as a new independent statutory body outside of the HSE to regulate the nuclear power industry, formally responsible in law for delivering regulatory functions. The creation of the ONR as a statutory body will consolidate the regulation of civil nuclear and radioactive transport safety and security regulation through one organisation. Pending the legislation, and in the interim, the HSE has established the ONR as a non-statutory body. The Government will review the functions and processes of the interim body in order to inform its planned legislation.

operational period (of a disposal facility)

The period during which a disposal facility is used for its intended purpose, up until closure.

passive safety

Not placing reliance on active safety systems and human intervention to ensure safety.

plutonium (Pu)

A radioactive element occurring in very small quantities in uranium ores but mainly produced artificially, including for use in nuclear fuel, by neutron bombardment of uranium.

post-closure period (of a disposal facility)

The period following sealing and closure of a facility and the removal of active institutional controls.

radioactive decay

The process by which radioactive material loses activity, e.g. alpha activity naturally. The rate at which atoms disintegrate is measured in becquerels.

radioactive material

Material designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity.

radioactive waste

Any material contaminated by or incorporating radioactivity above certain thresholds defined in legislation, and for which no further use is envisaged, is known as radioactive waste.

Radioactive Waste Management Limited (RWM)

A wholly owned subsidiary of the NDA, established to design and build an effective delivery organisation to implement a safe, sustainable and publicly acceptable geological disposal programme. Ultimately, RWM will evolve under the NDA into the organisation responsible for the delivery of the GDF. Ownership of this organisation can then be opened up to competition, in due course, in line with other NDA sites

radioactivity

Atoms undergoing spontaneous random disintegration, usually accompanied by the emission of radiation.

radionuclide

A radioactive form of an element, for example carbon-14 or caesium-137.

retrievability

A feature of the design of a GDF that enables the waste to be withdrawn, even after the disposal vaults have been backfilled

safety case

A 'safety case' is the written documentation demonstrating that risks associated with a site, a plant, part of a plant or a plant modification are ALARP and that the relevant standards have been met. Safety cases for licensable activities at nuclear sites are required as license conditions under NIA65.

safety function

A specific purpose that must be accomplished for safety.

shielded waste package

A shielded waste package is one that either has in-built shielding or contains low activity materials, and thus may be handled by conventional techniques.

shielding

Shielding is the protective use of materials to reduce the dose rate outside of the shielding material. The amount of shielding required to ensure that the dose rate is ALARP will therefore depend on the type of radiation, the activity of the source, and on the dose rate that is acceptable outside the shielding material.

stack (of waste packages)

A stack of waste packages placed vertically one on top of each other.

surface contaminated object (SCO)

A solid object which is not itself radioactive but which has radioactive material distributed on its surfaces.

transport package

The complete assembly of the radioactive material and its outer packaging, as presented for transport.

Transport Regulations

The IAEA Regulations for the Safe Transport of Radioactive Material and/or those regulations as transposed into an EU Directive, and in turn into regulations that apply within the UK. The generic term 'Transport Regulations' can refer to any or all of these, since the essential wording is identical in all cases.

transport system

The transport system covers the transport modes, infrastructure, design and operations. It can be divided in two main areas; the transport of construction materials, spoil and personnel associated with building a GDF and the more specialised transport of the radioactive waste to a GDF by inland waterway, sea, rail and/or road.

unshielded waste package

A waste package which, owing either to radiation levels or containment requirements, requires remote handling and must be transported in a reusable transport container.

uranium (U)

A heavy, naturally occurring and weakly radioactive element, commercially extracted from uranium ores. By nuclear fission (the nucleus splitting into two or more nuclei and releasing energy) it is used as a fuel in nuclear reactors to generate heat.

Uranium is often categorised by way of the proportion of the radionuclide uranium-235 it contains. The categories generally used in this guidance are:

- depleted uranium: <0.71% uranium-235;
- natural uranium: ~0.71% uranium-235;
- low enriched uranium: Up to ~5% uranium-235; and
- highly enriched uranium: >5% uranium-235.

waste acceptance criteria (WAC)

Quantitative and/or qualitative criteria, specified by the operator of a disposal facility and approved by the regulator, for solid radioactive waste to be accepted for disposal.

waste container

Any vessel used to contain a wasteform for disposal.

wasteform

The waste in the physical and chemical form in which it will be disposed of, including any conditioning media and container furniture (i.e. in-drum mixing devices, dewatering tubes etc) but not including the waste container itself or any added inactive capping material.

waste package

The product of conditioning that includes the wasteform and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared in accordance with requirements for handling, transport, storage and/or disposal.

waste packager

An organisation responsible for the packaging of radioactive waste in a form suitable for transport and disposal.



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