

Waste Package Specification and Guidance Documentation

Guidance on the design of waste containers
for waste packages containing low heat
generating waste

December 2019

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Waste Package Specification And Guidance Documentation

Guidance on the design of waste containers for waste packages containing low heat generating waste

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 Limited (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.

The Specification for Waste Containers for the Packaging of Low Heat Generating Waste (WPS/430) provides a specification for waste containers that can be used for the packaging of low heat generating waste for transport to and disposal in a geological disposal facility. This document expands on those requirements and provides guidance on the development of waste containers to meet them. The different sections and sub-sections of this document are intended to be stand-alone and can be read independently, of one another so that the reader can readily access the relevant information.

The WPSGD is subject to periodic enhancement and revision. Users are therefore advised to refer to www.gov.uk/guidance/generic-waste-package-specification to confirm that they are in possession of the latest version of any documentation used.

WPSGD Document Number WPS/890 – Version History

Version	Date	Comments
WPS/890/01	October 2018	New document issued to provide guidance in support of WPS/430. Aligns with Generic Specification for waste packages containing low heat generating waste (NDA/RWM/068) as published August 2012.

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Abbreviations and acronyms used in this document

AAR	Alkali-Aggregate Reaction
ACR	Alkali-Carbonate Reaction
ADI	Austempered Ductile Iron
ALARP	As Low As Reasonably Practicable
ASME	American Society of Mechanical Engineers
BAT	Best Available Technique
BS	British Standard
CARES	Certification Authority for Reinforcing Steels
CCA	Crushed Concrete Aggregate
CGI	Compacted Graphite Iron
DCI	Ductile Cast Iron
DER	Delayed Ettringite Formation
DSS	Disposal System Specification
EBW	Electron Beam Weld
EN	European Standard
GDF	Geological Disposal Facility
GDFD	Generic Disposal Facility Designs
GGBS	Ground Granulated Blast furnace Slag
GTSD	Generic Transport System Design
HAZ	Heat Affected Zone
HEPA	High Efficiency Particulate in Air filter
HSE	Health and Safety Executive
HSS	High Speed Steel
IAEA	International Atomic Energy Agency
IP	Industrial Package
ISO	International Organization for Standardization
ITP	Inspection and Test Plan
LHGW	Low Heat Generating Waste
LSA	Low Specific Activity

MAG	Metal Active Gas
MBGWS	Miscellaneous Beta Gamma Waste Store
MC-SLD	fib Model Code for Service Life Design
MIG	Metal Inert Gas
MPI	Magnetic Particle Inspection
NDA	Nuclear Decommissioning Authority
NDT	Non-Destructive Testing
NSCS	National Structural Concrete Specification for Building Construction
ONR	Office for Nuclear Regulation
PCE	Polycarboxylate Ether
PRE	Pitting Resistance Equivalent
QSRMC	Quality Scheme for Ready Mixed Concrete
RA	Recycled Aggregate
RWM	Radioactive Waste Management Limited
SCO	Surface Contaminated Object
SQEP	Suitable Qualified and Experienced Person
SWTC	Standard Waste Transport Container
TCSC	Transport Container Standardisation Committee
TIG	Tungsten Inert Gas
W/C	Water-Cement Ratio
WPS	Waste Package Specification
WPSGD	Waste Package Specification and Guidance Documentation

1. Introduction

The Nuclear Decommissioning Authority (NDA) has established Radioactive Waste Management Limited (RWM) as the body responsible for implementing UK Government policy for the management of higher activity radioactive wastes, as set out in *Implementing Geological Disposal – Working with Communities* [1], in England and *Geological Disposal of Higher Activity Radioactive Waste: Working with Communities* [2], in Wales. These policy documents outlines a framework for managing higher activity radioactive wastes 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 Disposal System Specification (DSS) [3]; which defines the requirements for all waste packages which are destined for geological disposal
- The Generic Specifications; which apply the high-level packaging requirements defined by the DSS to waste packages containing a specific type of waste
- The Waste Package Specifications (WPS); which apply the general requirements defined by a Generic Specification to waste packages manufactured using standardised designs of waste container.

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 the RWM website.¹

The WPSGD includes a range of WPS for different waste package types together with explanatory material and guidance that users will find helpful when it comes to application of the WPS to practical packaging projects. 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 [4].

¹ www.gov.uk/guidance/generic-waste-package-specification

The Specification for Waste Containers for the Packaging of Low Heat Generating Waste (WPS/430) (hereafter Waste Container Specification) [5] has been developed to define the required properties of the waste containers that can be used for the packaging of low heat generating waste (LHGW).² The requirements specified in the Waste Container Specification are based on the high-level requirements for waste containers given in the Generic Specification for Waste Packages containing Low Heat Generating Waste [6].

This document expands on the requirements defined in the Waste Container Specification and provides guidance on the development of waste containers to satisfy these requirements.

The Waste Container Specification and this document should be read in conjunction with the following other documents from the WPSGD:

- The WPS for waste packages containing LHGW (for example, [7])
- Guidance on the achievement of the requirements specified by the WPS [8,9]
- The wasteform specification for waste packages containing LHGW [10]
- Guidance on the production of encapsulated and unencapsulated wasteforms [11,12].

Scope of document

This document provides good practice design guidance for waste containers for LHGW. This good practice guidance is based on RWM's experience of the performance required from a waste container in order to achieve acceptable performance of a waste package during transport to a GDF, as well as the GDF operational and post-closure phases. The requirements on waste container performance that are derived from the need for interim storage, and transport related to interim storage, are not explicitly identified in this document. Such requirements should be considered by a waste container manufacturer in addition to the guidance provided. However, it is envisaged that the requirements relating to achieving the required waste package performance during transport to a GDF, and during the GDF operational and post-closure periods will be bounding.

² This broad category of waste includes intermediate level waste (ILW), and other wastes with similar radiological properties.

Structure of document

This document presents guidance in the following key areas:

- Design process and design management (Section 2)
- Selection of waste package type (Section 3)
- Material (Section 4)
- Designing a waste container to meet the requirements for waste packages for the packaging of LHGW (Section 5), including sub-sections for different areas of requirements
- Manufacture (Section 6)
- The use of codes and standards in waste container design (Section 7)
- The use of calculations in waste container design (Section 8)
- Design and manufacturing information requirements (Section 9).

Where guidance is specific to a particular type of waste container, the document has been further structured with dedicated sub-sections. The various sections and sub-sections are intended to be stand-alone; they can be read independently of one another so that the reader can readily access the relevant information.

Definition of “Relevant Good Practice”

The present document aims to define good engineering practice for the design of waste containers. As such, it defines “relevant good practice” rather than “best practice”.

In Assessing Compliance with the Law in Individual Cases and the Use of Good Practice [13], HSE defines good practice as:

“...the generic term for those standards for controlling risk which have been judged and recognised by HSE as satisfying the law when applied to a particular relevant case in an appropriate manner.”

It states that:

“‘Good practice’, as understood and used by HSE, can be distinguished from the term ‘best practice’ which usually means a standard of risk control above the legal minimum.”

Principle RW.5 for Radioactive Waste Management – Storage of Radioactive Waste and Passive Safety from ONR’s Safety Assessment Principles (SAPs) [14], states that *“Radioactive waste should be stored in accordance with good engineering practice and in a passively safe condition.”* It also explains that *“The safety case should: ... demonstrate that radioactive waste is managed in accordance with relevant good practice and good engineering principles.”*

This document aims to define good engineering practice for the design of waste containers in line with this principle.

Provenance of good practice as defined in this document

The good practice defined in this document has been distilled from the extensive experience of RWM and the authors of this document in the design, analysis, manufacture, research and assessment of a wide range of waste container designs over many years. This has been supplemented by the expertise and experience from the authors' involvement in the design, fabrication and construction of steel and reinforced concrete civil engineering structures. In a number of areas, the good practice defined in this document also builds on various guidance documents developed previously by RWM and RWM's predecessors.

2. Design process and design management

A waste container design is the outcome of a design process, just like any other designed items. A sound process is key to achieving a sound design.

A design process typically consists of four stages:

- Trigger and definition
- Brief and set-up
- Development
- Evaluation

The precise details of the design process depend on the culture and the established practice of the organisation carrying out the design, and on the specific needs of the design project.

Assuming that the design project is to develop a new waste container based on one of RWM's standard package types, the four stages could be expected to include the following components:

Trigger and definition:

- Define the problem
- Define the success criteria
- Define project constraints – time, budget, resource, priority
- Define the design process
- Identify key stakeholders, including external approvals and specialist input
- Risk assessment
- Economic assessment
- Develop the business case and obtain approval.

Brief and set up:

- Identify the requirements
 - requirements during packaging, storage, transport, disposal (including GDF operations, backfilling and post-closure)
 - requirements from regulatory, legal and other bodies
 - requirements from the wasteform developers

- Establish interfaces – with the container manufacturer, with those developing the waste management solution (for example, treatment and wasteform), with the operator
- Develop the functional specification
- Develop the design specification
- Define the project team
- Define internal and external approval processes
- Define the output
- Define information control and document management requirements
- Define quality assurance procedures
- Define environmental requirements
- Develop the delivery plan and programme.

Development:

- Feasibility studies and optioneering
- Conceptual design
- Scheme design
- Detailed design
- Prototype manufacturing and testing
- Value engineering and optimisation.

Evaluation:

The design, and the design process, should be reviewed at suitable times during the project (for example, after feasibility studies, after conceptual design) and at the end of the project, so that lessons can be learnt and used to improve the remaining steps of the project and future projects.

If the work is to adapt an existing design, or to develop a container for a non-standard package type, the length and complexity of the process will be different. If the work involves developing a container using a new material for which the organisation has no corporate experience, additional research will be required and the process can be expected to take longer.

In addition to the components listed above, the design process should also include the following:

- Hold Points, when specific requirements need to be satisfied before the process can proceed further
- Design Reviews, which should be carried out at key stages of the project to confirm the validity of the design, to identify problems, to challenge assumptions, and to identify solutions; suitable personnel from appropriate disciplines within the team, and where appropriate from outside the team, should be engaged in these reviews
- Delivery Plan, which should identify key inputs, outputs, timescales, resources and effort, critical path, float, interdependencies between tasks, interdependencies between different disciplines, as well as design reviews and stakeholder engagements; the plan should be reviewed regularly and communicated effectively.

Often the waste container design process is part of the packaging campaign, which could be a part of a site-wide waste management process. The waste container design process needs to be well integrated into the wider packaging campaign.

As the container will be used to package waste, and will be used by those who will be packaging the waste, there must be clear interface between the container design team and the team which is responsible for designing the waste conditioning process, and also the operators who will use the waste container.

Waste containers are subject to different sets of requirements during the different stages of their lifespan: manufacturing, waste loading/conditioning, on-site transport, on-site storage, public domain transport and disposal at the GDF. As the requirements at each stage may be different, the performance criteria may also vary. The requirements and criteria at each stage should therefore be carefully mapped out and addressed, for example, in a functional specification or in a set of User and System Requirements Documents. The requirements should then be condensed down to become a design specification against which the designers will carry out the design. The design specification should include all the design requirements, including, as far as possible, assumptions, methodology, basis of design, and input and output from the design activity.

3. Selection of waste package type

Different wastes call for different processing methods, and different waste container types will be suitable for different types of wastes.

There are three basic types of waste packages:

1. **Shielded waste packages:** Reinforced concrete containers, or thin-walled metal containers with integral concrete shielding, and cement encapsulated wasteforms. Typically used to package low specific activity, lower radiation level and non-fissile or fissile-excepted LHGW. They can be handled without remote handling techniques and are transported as IP-2 packages to IAEA Transport Regulations [15].
2. **Robust shielded waste packages:** Thick walled (that is, 50 mm or greater) ductile cast iron (DCI) with unencapsulated wasteforms. Typically used to package lower radiation level LHGW, and non-fissile or fissile-excepted LHGW that does not need encapsulation. They can be handled without remote handling techniques. They can be transported with or without a reusable transport container as either a Type B or IP-2 package to IAEA Transport Regulations depending upon their contents.
3. **Unshielded waste packages:** Thin walled metal containers with cement encapsulated wasteforms. Typically used to package higher specific activity, higher radiation level or fissile LHGW. They generally require remote handling and transport in reusable transport containers as a Type B package to IAEA Transport Regulations.

The choice of waste package type should take into consideration the nature of the waste to be packaged, the intended wasteform that will be produced, the containment requirements, the shielding requirements, the waste processing requirements, the handling requirements, constraints on package mass and dimensions, transport requirements, and cost.

On the most fundamental level, the choice of waste package type for waste types is typically as follows:

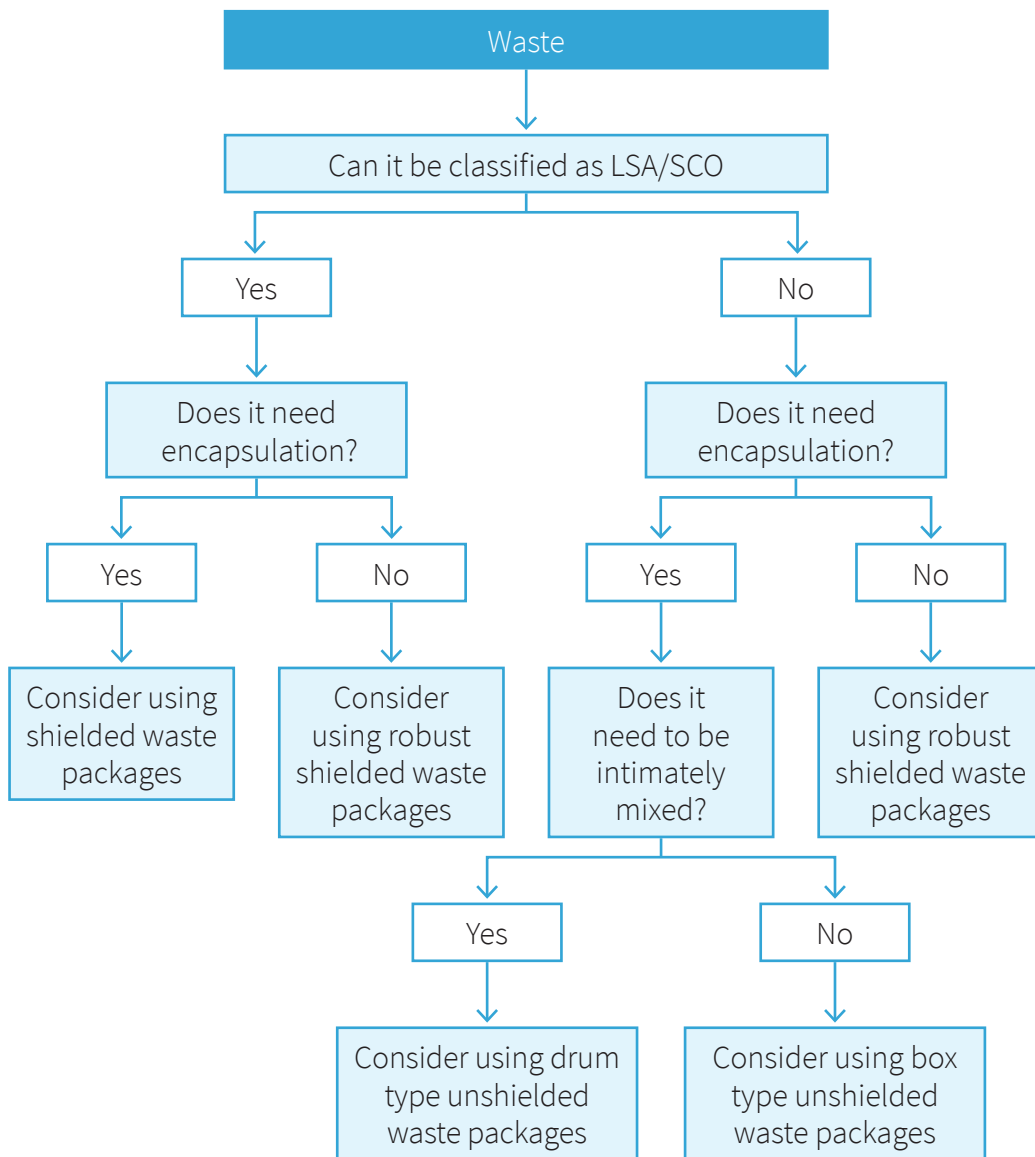
- For wastes which satisfy the definition of Low Specific Activity (LSA)³ – Surface Contaminated Object (SCO)⁴ materials and need to be encapsulated, the use of shielded waste packages should be considered. For wastes which satisfy the definition of LSA-SCO materials but do not need to be encapsulated, the use of robust shielded waste packages should be considered.
Typically, these waste packages would satisfy the requirements of IP-2 packages under the IAEA Transport Regulations [14]. The quantity of LSA material or SCO material will need to be restricted so that the external radiation level requirement of IP-2 packages is satisfied. The use of IP-2 packages avoids the need and cost of remote handling facilities and of Type B transport containers.
- For wastes that do not satisfy the LSA-SCO requirements and need to be intimately mixed with an encapsulation medium to form a wasteform, for example mobile wastes such as sludges, a drum type unshielded waste package (rather than a box type waste package) should be considered as it allows mixing within the entire cavity of the drum with no stagnant corners.
- For solid wastes (especially solid wastes that consist of large items) that do not satisfy the LSA-SCO requirements but need to be encapsulated in an encapsulation medium without needing to be intimately mixed, a box type unshielded waste package (rather than a drum type waste package) should be considered as it can accommodate large payload and it has a large opening.
- For wastes that do not satisfy the LSA-SCO requirements and do not require encapsulation, a robust shielded waste package should be considered.

This is illustrated in the decision tree in Figure 1 overleaf.

3 LSA – radioactive material that by its nature has a limited specific activity, or radioactive material for which limits of estimated average specific activity apply.

4 SCO – a solid object that is not itself radioactive but which has radioactive material distributed on its surface.

Figure 1: Decision tree for the selection of waste package type



Among the many factors that need to be considered in the choice of a waste package type, it has been found that the choice between shielded and unshielded package is one of the most significant ones, as this has important implications for the design of the waste treatment process and packaging facilities, as well as the design of the interim storage facilities. The cost/spend profile of a waste management campaign may strongly influence the choice, and conversely, the choice has significant implications for the cost/spend profile of the waste management campaign.

4. Material

4.1 Introduction

Unshielded waste packages are typically manufactured using thin walled (that is, a few mm thick) metal containers. Stainless steels have been found to be satisfactory materials for these containers due mainly to the combination of strength, stability in the envisaged environments and long-term integrity, so that the design functions of the waste container can be satisfied with minimal material thickness.

Shielded waste packages are typically manufactured using either reinforced concrete containers or thin-walled metal containers with integral concrete shielding. For the latter, stainless steels have been found to be satisfactory materials for the same reasons as discussed above for waste containers for unshielded waste packages. The required shielding could be achieved by increasing the wall thickness of the waste container, but as the structural requirements of the waste container can be satisfied with a thin-walled design, it is more cost effective to achieve the required shielding using a lower cost material. For this reason, designs using concrete as shielding have been proposed.

In the case of reinforced concrete containers, the choice of reinforced concrete can be attributed to it being a common construction material with well-established good practice in design and manufacture, as well as being attractive economically.

Robust shielded waste packages are typically manufactured using thick walled (that is 50 mm or greater) DCI containers. DCI containers have been found to be a viable option as the economics of the whole life cycle can be competitive in comparison with the more conventional waste encapsulation in thin-walled steel containers. So far, such containers have only been produced using DCI, but with the right manufacturing technique and manufacturer, steel containers manufactured by fabrication (that is, steel plates and welded) rather than casting, could also be technically and economically feasible. Steel containers manufactured by forging would also be possible in terms of satisfying technical requirements, but this would be cost prohibitive.

In selecting the materials for the manufacture of waste containers, the following should be considered by the designer:

- The long-term durability of the material under the particular exposure conditions
- The mechanical and thermal behaviour of the material
- The design requirements to achieve the specified waste container performance
- The fabrication/manufacturing characteristics of the material
- The cost of materials and fabrication.

The following sub-sections present guidance on stainless steel, reinforced concrete and cast iron in turn. Note that the structure of the sub-sections differs, as the route to a specific suitable grade or formulation differs for each material type. For example, for stainless steel, it is appropriate to select one of a number of specific grades, while for concrete it is common to decide on a strength grade before deciding on the formulation, and for DCI the choice of formulation would depend on the properties required.

4.2 Stainless steel

4.2.1 Introduction and material grades

The term stainless steel is defined as an alloy of iron that contains a minimum of 10.5% chromium. The chromium reacts with oxygen to produce a thin oxide on the surface of the steel, known as the passive layer, and promotes the stainless steel's inherent corrosion resistance. Other elements such as nickel and molybdenum may be added to impart other useful properties such as enhanced formability and increased corrosion resistance.

There are many different stainless steel alloys, which are sub-divided into the following five groups according to their metallurgical microstructure:

- Austenitic
- Ferritic
- Martensitic
- Duplex (which has a metallurgical structure consisting of a balance of two phases – austenite and ferrite)
- Precipitation hardening.

Of these, austenitic and duplex stainless steels are considered most suitable for use in the design and manufacture of waste containers, and specific grades are discussed below.

In practice, austenitic stainless steel, typically Grade 1.4404 (which is broadly equivalent to 316L), has been extensively used for the manufacture of containers for 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 [16] in atmospheric and controlled storage environments, as well as in contact with typical wastes and conditioning materials. This means the material thickness allowance for corrosion is less than would be required with carbon steels. This is beneficial in terms of reducing cost and reducing waste container mass.
- Strong yet ductile, so can be readily cut, formed and machined, especially when used in relatively thin sections.
- Weldable by standard methods without the need for extensive pre- or post-weld heat treatment. As a consequence, suitably experienced commercial fabrication shops are readily available.

In addition, common grades of stainless steel are widely used in other industries and so they are readily available in a range of product forms, and have a good long-term track record in analogous industrial applications.

Other stainless steels, notably Grade 1.4306 (or equivalent, for example, 1.4307), 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 improved corrosion resistance, and hence can be used in lesser thicknesses than austenitic stainless steels. Duplex steels are, however, potentially more difficult to form and weld.

Although the choice of stainless steel alloys is potentially wide, the following alloys have been identified by RWM as possible candidates for waste containers, having suitable corrosion performance combined with mechanical properties for the manufacture of waste containers:

- Austenitic stainless steel to grade 1.4404 (which is broadly equivalent to 316L)
- Austenitic stainless steel to grades 1.4306/1.4307 (which is broadly equivalent to 304L)
- Lean duplex stainless steel to grade 1.4162
- Duplex stainless steel to grade 1.4462.

4.2.2 Durability

Corrosion is a major potential threat to the ability of a waste container to maintain an adequate level of integrity for the required timescale. The requirement is that the integrity of the waste container shall be maintained for a period of 150 years and should be maintained for a period of 500 years following manufacture of the waste package.

Stainless steels are generally corrosion resistant and will perform satisfactorily in most environments. However, the actual corrosion resistance afforded is dependent upon the specific alloy and its chemical composition, and it follows that each stainless steel alloy has slightly different characteristics in terms of corrosion resistance.

When selecting a material for the fabrication of waste containers, designers will need to understand both the internal and external environments that the container will be subjected to, and determine which degradation mechanisms can take place in those environments. The response of waste package designers to this requirement has generally been to manufacture waste containers from austenitic stainless steel to grade 1.4404 [17] or its equivalent. The corrosion performance and mechanical properties of this material are generally regarded as optimal for the packaging of radioactive waste, and this performance has been demonstrated by experience and research [15].

Duplex stainless steel, notably grade 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 surface finish of the material will also play key roles in maintaining the integrity of the waste container.

A variety of corrosion mechanisms can affect the integrity of stainless steel waste containers, some of which are described below:

- **General corrosion**, or uniform corrosion, is the uniform loss of metal over an entire surface. The rates of general atmospheric corrosion of stainless steels are widely reported, and corrosion rates from $< 0.2 \mu\text{m}/\text{year}$ ($> 5,000 \text{ years}/\text{mm}$) to $3 \mu\text{m}/\text{year}$ ($300 \text{ years}/\text{mm}$) have been observed in industrial/urban and marine environments. Initial measurements from longer-term testing suggest corrosion rates of $\sim 0.01 \mu\text{m}/\text{year}$ 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.
- **Pitting corrosion** is a localised form of corrosion by which cavities or “holes” are produced in the material. It occurs as a consequence of localised breakdown in the surface passive layer, for example as a result of exposure to chloride ions from seawater, although other halides and anions can have a similar effect. A measure of pitting resistance can be determined by the Pitting Resistance Equivalent (PRE). Various formulae have been proposed to define PRE and one of the more commonly used (from [18]) is as follows and can be used to rank the performance of different alloys:

$$\text{PRE} = 1 \times \% \text{Cr} + 3.3 \times \% \text{Mo} + 16 \times \% \text{N}$$

The higher the PRE value, the greater the pitting resistance. The PRE for the grades listed above is shown in Table 1 below [19]. Among the grades listed, duplex stainless steel grade 1.4462 has the highest pitting corrosion resistance.

Table 1: Approximate PRE values based upon chemical composition

Grade	PRE
Austenitic stainless steel grade 1.4404	24
Austenitic stainless steel grade 1.4306/1.4307	18
Lean duplex stainless steel grade 1.4162	26
Duplex stainless steel grade 1.4462	35

- **Crevice corrosion** refers to the localised attack on a metal surface at, or immediately adjacent to, the gap or crevice between two joining surfaces. This can occur in similar environmental conditions to pitting corrosion. Corrosion initiates more easily in a crevice than on a free surface because the conditions for maintaining the passive film are restricted.

Crevices formed between waste container components, in the container lid area or between the wastefrom and the inside of the container, should be avoided during waste container and waste package design. Similarly, welded connections should be detailed to avoid the creation of crevices. Localised corrosion mechanisms are also dependent upon the presence of surface contaminants, in particular, chlorides and care should be taken during manufacture to avoid or remove surface contaminants. Work has been carried out to investigate these effects and this is presented in [20].

- **Stress corrosion cracking**, as the name implies, requires the simultaneous presence of tensile stress and specific environmental conditions. 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 [21]. 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 wastefroms should, therefore, be kept to a minimum and careful consideration be given to possible corrosion mechanisms if it exceeds 100 ppm. Duplex stainless steels have a greater resistance to stress corrosion cracking than austenitic stainless steels.

- **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.

To assist waste package designers in this area, guidance has been produced on the general corrosion properties of stainless steel [15].

4.2.3 Fabrication characteristics

The fabrication of a waste container with the required dimensions, shape and containment properties will place demands on a number of properties of the materials selected. For instance, the fabrication of waste containers from metal may involve forming (for example, bending, spinning), joining (for example, welding) and machining (for example, tapping and threading of bolt holes).

Some specific aspects of stainless steel fabrication for the waste container designer to consider when selecting materials are as follows:

- Stainless steels readily work-harden during cold-working. This particular characteristic can affect both machining and cold-forming operations (bending and pressing). For example, the power requirements for bending stainless steel might be expected to be higher than for carbon-steels and, equally, the degree of spring-back is greater in stainless steels.
- Stainless steels can be formed to tight radii, with typical internal bend radii of $1T$ for austenitic stainless steels and $2T$ for duplex stainless steels, where T is the plate thickness. The larger internal bend radii in duplex stainless steels are due to its greater spring-back as well as lower ductility in comparison with austenitic stainless steels.
- Guidance on welding and techniques that may be employed during the fabrication of stainless steel containers is given in [22]. One aspect the designer may wish to consider during any design development is the potential for distortion associated with welding. Like other metals, stainless steels suffer distortion due to welding, but the degree of distortion is typically greater than that associated with carbon steels. This is particularly so with austenitic stainless steels, which have a lower coefficient of thermal conductivity and higher coefficient of thermal expansion than carbon steel. As a consequence, higher expansions in smaller heat affected zones (HAZ) result in more distortion.
- The choice of welding consumable is essential to maintain the inherent corrosion resistance of the different stainless steels. Commercially available welding consumables are intended to give weld deposits with equivalent corrosion resistance and mechanical properties to that of the base alloy.

4.2.4 Cost and availability

In the selection of an appropriate stainless steel for waste containers, material cost is an important criterion. The relative degree of alloying, that is, the amount of chromium, nickel and molybdenum contained in each alloy has a direct influence on the respective cost. Costs associated with the alloying, known as the alloy surcharge, are published by stainless steel manufacturers on a monthly basis. Given that costs are constantly changing, it is recommended that designers consult with stainless steel manufacturers to assess costs during design development to assess the relative impact of their preferred alloy selection.

Such investigation of cost should also consider that waste packages are likely to be procured over an extended period, and ongoing availability of the material at a similar price may be equally important.

For manufacturing campaigns for a large number of waste containers or that span a long timescale, contingency of stainless steel supply must be considered. If specific steels are required, multiple suppliers should be identified to reduce risk. Manufacturers should have a robust supplier qualification process in place to avoid reliance on a single source.

4.2.5 Choice of stainless steel

As has already been noted above, the following alloys have been identified by RWM as possible candidates for the manufacture of waste containers:

- Austenitic stainless steel to grade 1.4404 (which is broadly equivalent to 316L)
- Austenitic stainless steel to grade 1.4306/1.4307 (which is broadly equivalent to 304L)
- Lean duplex stainless steel to grade 1.4162
- Duplex stainless steel to grade 1.4462.

Strength requirements and cost, and especially the balance between a material's strength and cost, should be the main consideration in the choice between the austenitic and duplex grades of stainless steels.

The price per tonne and 0.2% proof stress of these grades of austenitic and duplex stainless steel are summarised in Table 2 below:

Table 2: Comparison of 0.2% proof stress and cost of different grades of stainless steel

Material	0.2% proof stress	Approximate price per tonne (see note below)
1.4306 Austenitic stainless steel	200 MPa [17]	£2200
1.4404 Austenitic stainless steel	220 MPa [17]	£2900
1.4162 Lean duplex stainless steel	480 MPa [17]	£2350
1.4462 Duplex stainless steel	460 MPa [17]	£3100

Note: Prices per tonne are a broad estimate, based on an assumed base price supplied by Outokumpu and an alloy adjustment factor dependent on the chemical composition of the steel, both supplied in December 2017.

Rather than based on cost per tonne on its own, the choice should be based on a consideration of the balance between a material's strength and cost per tonne. The duplex stainless steel range has a 0.2% proof stress that is more than double those of grades 1.4306 and 1.4404. The lean duplex is about 7% more expensive than 1.4306 but about 20% cheaper than grade 1.4404. The 1.4462 duplex is more expensive than 1.4306 by about 40% and more expensive than 1.4404 by about 7%. To achieve the same safety margin in the design, using a lean duplex stainless steel requires thinner sections and thus incurs a lower material cost.

Regarding material costs, it should also be noted that duplex stainless steels have historically had lower price volatility in the market than 1.4306 and 1.4404 stainless steels due to their lower nickel content.

In addition to cost and mechanical properties, duplex stainless steels also have a higher chromium content than comparable austenitic stainless steels, and the use of nitrogen as an alloying element means that duplex stainless steels generally have a greater resistance to localised corrosion.

In addition to strength requirements and material cost, the following are additional factors that should also be considered in the choice between the austenitic grades and the duplex grades identified above:

- Duplex grades of stainless steel will pose more burden to the tooling, and may involve higher tooling cost, due to their higher strength
- Duplex grades of stainless steel are potentially more difficult to form and weld
- Additional certification testing is needed for duplex grades of stainless steel (over and above those required for austenitic stainless steels) for the qualification and approval of welding procedures; tests typically include determination of corrosion resistance and the presence of detrimental intermetallic phases
- Duplex grades of stainless steel have a lower elongation to failure (20-30%) than austenitic grades of stainless steel (40-45%); in performance scenarios where ductility is important, this difference should be considered.

4.3 Reinforced concrete

4.3.1 Introduction

Reinforced concrete is a composite consisting of concrete with a secondary constituent material (for example, steel reinforcement bars or steel fibres) to provide tensile resistance. Guidance on concrete and reinforcement materials are discussed in the following sub-sections, followed by guidance to achieve integrity and means to minimise the risk of early age cracking.

The design of concrete structures should adhere to the requirements of well-established international structural design codes such as Eurocode 2 [23].

4.3.2 Concrete

Strength and basic definition of concrete

Concrete strength is a key parameter in concrete structural design. In Eurocode 2, the concrete strength value to be used in the design is termed f_{cd} , design compressive strength, and is defined as:

$$f_{cd} = \alpha_{cc} f_{ck} / \gamma_c$$

where f_{ck} is the specified cylinder characteristic compressive strength of the concrete, and α_{cc} and γ_c are coefficients to take account of long-term effects on the compressive strength and unfavourable effects resulting from the way the load is applied.

In Eurocode 2, the characteristic compressive strength is specified by means of a dual concrete compressive strength class, which expresses the required strength as both the 28 day cylinder strength and the equivalent 28 day cube strength. For example, specifying a strength class C32/40 to BS EN 206 [24], means that the minimum characteristic cylinder strength is 32 N/mm² and the minimum characteristic cube strength is 40 N/mm² at 28 days.

For design purposes, Eurocode specifies that cylinder strength should be used. For the purposes of specifying concrete to a manufacturer and for quality control, either cylinder strength or cube strength is acceptable, but just one should be used throughout the project.

In the UK, the national provisions given by BS 8500-1 [25] and BS 8500-2 [26] complement the scope of BS EN 206 in terms of concrete specification, performance, production and conformity, and should be used as they provide further recommendations on the permitted cement types, materials, methods of testing and quality control procedures.

Constituent materials

Constituent materials for concrete should conform to the current versions of BS EN 206 and BS 8500. Other recognised national standards (for example, ACI 301, ACI 349) may be used provided that it can be demonstrated that the resultant concrete will be equivalent to that produced in accordance with BS and EN standards. The requirements for the components of concrete from BS EN 206 and BS 8500 are summarised below:

Cements and combinations

There are a number of cements which can be used as a constituent for concrete.

In addition to Portland cement clinker, suitable cements could also contain inorganic materials or additions which can improve properties such as durability and low heat development. Cements can also be produced with additions such as limestone, fly ash, ground granulated blastfurnace slag and silica fume (blended cements). The term “cement” is generally reserved for factory-produced cementitious materials. An equivalent “combination” refers to a blend of the same materials, in the same proportions, but combined at the concrete mixer from the individual constituent materials (for example, Portland cement + fly ash).

A high alkalinity reserve is required of the concrete matrix to protect the steel reinforcement from corrosion whilst ensuring that the concrete remains an effective barrier to radionuclide migration. In order to maintain high alkalinity over a long period it is recommended that the level of constituents within the cement or the equivalent combination is restricted to the following choices, which omit types more prone to neutralisation by carbonation:

- Portland cement (CEM I)
- Portland-limestone cement (IIA-L)
- Portland-slag cement (IIA-S or IIB-S)
- Portland-fly ash cement (IIA-V, IIB-V, IIB-V+SR)
- Portland-silica fume cement (IIA-D)
- Blastfurnace cement (IIIA) with ground granulated blastfurnace slag (GGBS) content not exceeding 60%.

The selection of cement, or equivalent combination, should take account of any practical requirements such as early strength gain, temperature control and curing needs. For example, CEM I cement concretes will lead to early strength gain, higher temperatures whilst curing and lower curing times when compared with IIB-V or IIIA concretes.

Aggregates

Aggregates for concrete should be in accordance with Clause 4.3 of BS 8500-2: 2015 [25], BS EN 12620 [27] and PD 6682-1 [28]. They should be naturally impermeable and mechanically strong, and of normal or heavy weight. Crushed concrete aggregate (CCA) or recycled aggregate (RA) should not be used as their suitability for this long-term application has not yet been established, particularly in relation to exposure to aggressive ground conditions.

Where high-density concrete is required for radiation shielding, aggregates made with high-density ores such as barytes and haematite, or manufactured products, such as steel shot, can be used.

The maximum size for coarse aggregate should be in the range 10 – 32 mm to ensure compatibility with values in Eurocode 2. In choosing maximum aggregate size, account must be taken of the reinforcement density and spacing, and any other obstacles to concrete placement (for example, embedments) to ensure the concrete can flow freely between them.

Mixing water

Mixing water for concrete should comply with BS EN 1008 [29]. Recycled wash water from concrete production may be used if it can be shown that it does not have a negative effect on the properties of the fresh or hardened concrete.

Chemical admixtures

It is common to use chemical admixtures in concrete to increase strength and quality, and to facilitate placement. Chemical admixtures for concrete should be in accordance with BS EN 934-2 [30].

Water reducing/plasticising admixtures and/or superplasticising admixtures are often used to improve workability. However, use of these admixtures is subject to RWM agreement. RWM has produced a thematic guidance on the use of polycarboxylate ether (PCE) type superplasticisers for the packaging of LHGW, including their use in the manufacture of reinforced concrete waste containers [31]. This thematic guidance should be consulted.

Other admixtures, such as retarding agents, air-reducing agents, hydration stabilising admixtures, or shrinkage reducing admixtures should not be used unless their use has been agreed with RWM.

Composition

Compositional limits

Limits on the composition of concrete, for example minimum cement content and maximum water/cement ratio, should be in accordance with BS EN 206 [23] and BS 8500 as follows:

- In order to ensure long-term durability, the free water to cement ratio (or free water to combination ratio) should not be greater than 0.40. This reduces porosity and permeability, which are directly related with diffusion and leaching characteristics.
- In order to reduce the potential long-term drying shrinkage and consequential risk of cracking, the free water content should not be greater than $160 \text{ dm}^3/\text{m}^3$. The free water is the difference between the total water present in the fresh concrete and the water absorbed by the aggregates.
- In order to ensure a dense, closed structure concrete (that is, all space between aggregates filled with paste), the total cement or combination content should not be less than $270 \text{ kg}/\text{m}^3$.
- In order to reduce the risk of excessive heat development during hydration, and of alkali-aggregate reaction, the total cement or combination content should not be greater than $550 \text{ kg}/\text{m}^3$.

Chloride content

Corrosion of reinforcement in concrete due to chloride can only start once the chloride content at the steel surface has reached a certain level. In order to reduce the risk of premature depassivation of the steel reinforcement over the long period over which the integrity of waste containers is required, the initial chloride content of the concrete should not exceed 0.1% by mass for mild steel reinforcement and 0.4% by mass for stainless steel reinforcement. The initial chloride ion content of the concrete should be determined in accordance with BS EN 14629 [32].

Properties

Workability (consistence)

Constituent materials, mix design and consistence class should be chosen to provide workability properties that ensure full filling of moulds/formwork and full compaction.

Concrete that is prone to instability (for example, bleed, segregation or settlement) should not be used. Good segregation resistance, cohesiveness, flow and general good workability can be achieved through good mix design involving an appropriate choice of concrete composition and the use of suitable admixtures.

Self-compacting concrete does not require vibration or compaction when the concrete is placed, and therefore it is often used in heavily reinforced structures which offer limited access for “pokers” (vibration tools normally inserted into fresh concrete to facilitate compaction). If it is used, it should adhere to best practice as outlined in “The European Guidelines for Self-Compacting Concrete: Specification, Production and Use” [33] or equivalent. The type and amount of superplasticising admixtures should be in line with RWM thematic guidance WPS/926/01 [30]. It should be demonstrated by means of trials that the composition of self-compacting concrete is able to tolerate normal variations in properties and measured quantities of constituent materials without instability or loss of flow properties.

Elastic modulus, shrinkage and creep

In most reinforced concrete structural designs, the characteristic cylinder strength of the specified compressive strength class is also used to determine the design values for a number of other engineering properties, including tensile strength, static modulus of elasticity, shrinkage and creep. This is done by employing the expressions given by the relevant structural code, for example, Eurocode or ACI.

The static modulus of elasticity is highly dependent on the type of aggregate used. Consequently, when the elastic modulus is critical to the performance of the structure, it is recommended to carry out tests to obtain an accurate value rather than relying on an assumed value. A suitable test for the static modulus of elasticity is defined in BS EN 12390 13 [34].

Variation in properties such as elastic modulus, creep and shrinkage due to the inherent variability of concrete and its constituent materials is expected, and is generally accommodated by the safety margin in Eurocode 2.

In accordance with good practice, the 28 day drying shrinkage should be minimised through the use of low free water content, maximizing the proportion of aggregate and possibly using shrinkage-reducing admixtures. Drying shrinkage should not be greater than 300 $\mu\text{m}/\text{m}$ when tested in accordance with ISO 1920-8 [35].

Similarly, to obtain a good understanding of the creep behaviour of a concrete, tests should be carried out. A suitable test is defined in RILEM TC 107-CSP [36].

Freezing and thawing resistance

Concrete for container structures that may be exposed to freezing/thawing in moist conditions, or exposure to de-icing salt, salt spray or salt mist, should have an appropriate entrained air void system produced by the use of an air-entraining admixture, in accordance with BS 8500.

4.3.3 Reinforcement

Reinforcing bars

Reinforcing bars should conform to BS 4449 [37] and BS 8666 [37], and hold product certification from the Certification Authority for Reinforcing Steels (CARES).

If a superior level of elongation during plastic deformations is required, for example, to improve performance in impact accident scenarios, high-ductility class C steel in accordance with BS 4449 [38] should be considered.

If stainless steel reinforcing bars are used, class EN 1.4362 to BS 6744 [39] is recommended. EN 1.4362 is a duplex, austenitic-ferritic chromium-nickel stainless steel (X2CrNi23-4). It has a good combination of corrosion resistance, resistance to stress corrosion cracking, high tensile strength and yield strength.

Steel fibres

Instead of reinforcing bars, steel fibres could also be considered to reinforce concrete for waste container designs. The fibre's material properties (for example, elastic modulus, tensile strength) and geometrical properties (for example, length, diameter, type of anchor) affect the performance of reinforced concrete. There are a number of benefits in using steel fibres as reinforcement:

- The matrix is reinforced, thus providing higher impact fatigue, abrasion strength and tensile strength
- Concrete microcracking is reduced
- Higher durability when adopting non-corroding amorphous metal.

Steel fibres, where used, should comply with BS EN 14889-1 [40].

The design of concrete reinforced with steel fibres should be carried out in accordance with the following:

- fib Model Code 2010 [41], Section 5.6
- German Guideline for Steel Fibre Reinforced Concrete, Deutscher Ausschuß für Stahlbeton (DAfStb): Richtlinie Stahlfaserbeton, Edition 2010 [42]
- RILEM TC 162-TDF: Test and design methods for steel fibre reinforced concrete [43].

4.3.4 Design to achieve integrity

RWM requires that the integrity of the waste container shall be maintained for a period of 150 years and should be maintained for a period of 500 years following manufacture of the waste package.

To achieve the necessary degree of integrity during the waste container life, the materials should be selected in order to avoid and mitigate the risk due to:

- Internal expansive reactions in the concrete, for example, alkali-aggregate reaction and delayed ettringite formation
- Corrosion of the reinforcement bars due to depassivation caused by external agents, for example, carbonation or chloride induced corrosion during the surface storage period.

These are discussed below.

Avoidance of internal expansive reactions in the concrete

Alkali aggregate reaction (AAR) and delayed ettringite formation (DEF) can lead to expansion of concrete, which could be detrimental to the long-term integrity of the waste container. AAR involves deleterious chemical reactions between the alkalis in the paste and silica or carbonate constituents in the aggregate. DEF is a form of internal sulfate attack induced by exposure to excessive heat during curing.

Provisions to reduce the risk of internal expansive reactions due to AAR and DEF are as follows:

Alkali aggregate reaction

The risk of alkali-silica reaction should be mitigated in accordance with BRE Digest 330 [44]. Aggregates should have low or normal reactivity as defined in Digest 330.

The risk of alkali-carbonate reaction (ACR) should be mitigated by avoidance of dolomitic limestone aggregate with a mineralogical composition susceptible to reaction. UK limestone aggregates are generally not susceptible to ACR.

Delayed ettringite formation

One measure to reduce the risk of DEF is by ensuring that the temperature of the concrete during the early age hydration heat cycle does not exceed 65°C.

Concrete heated beyond this temperature, and in the presence of humidity in service may be susceptible to damaging expansion. This is the result of ettringite (calcium sulfoaluminate hydrate) formation, causing expansion pressures and disruption of the hardened paste. Furthermore, the risk is higher if highly reactive, highly alkaline cements with sufficient quantity of sulfates are present.

In theory, the adoption of cements or combinations containing fly ash, GGBS or silica fume may allow higher temperature limits. However, due to uncertainty over long-term performance, higher temperature limits should not be accepted.

There are specific performance tests that can be carried out to assess the expansion risk for concrete with respect to DEF at higher temperature limits, but this involves minimum periods of 12 months of immersion, which may need to be extended for an additional 15 months should significant expansion be measured. If required, the expansion risk at higher temperatures should be determined in accordance with the test method from Laboratoire Central des Ponts et Chaussées (LCPC) number 66 [45].

Avoidance of corrosion of the reinforcement bars due to depassivation caused by external agents

Provisions are given in BS 8500 for an approximate 100-year service life. As a service life longer than this is required of waste containers, verification that the selected concrete composition and reinforcement can achieve the required long-term integrity is recommended. This can be done through the application of durability design codes and standards such as the fib Model Code for Service Life Design (MC-SLD) [40] and ISO 16204 [46]. If needed, the definition of durability performance requirements, such as chloride diffusion coefficients or inverse effective carbonation diffusion coefficients, can be included as mix design parameters in the concrete mix specification.

For the prevailing deterioration mechanism (for example, carbonation or chloride-induced corrosion of reinforcement), modelling can be used to verify and demonstrate that corrosion of the reinforcement does not initiate. For the purpose of durability design, the initiation of corrosion is considered the durability limit state that should not be exceeded.

Probabilistic models such as the fib MC-SLD [35] can be used to justify that the selection of materials is appropriate. This verification is done by calculating that the minimum reliability level is achieved over the required integrity period. Requirements for parameters for use in probabilistic models for these containers are summarised in Table 3.

Table 3: Minimum reliability index required before corrosion of the reinforcement bars starts

Mechanism	Integrity period requirement (years)	Minimum reliability index, β	Exposure classes (BS EN 206)	Observations
Chloride attack ¹⁾	150 years or surface storage time	1.50	XS1 / XD1 – Moderate humidity and airborne chlorides	According to Eurocode – Basis of Structural Design [47], a minimum $\beta=1.50$ must be considered for serviceability limit state ³⁾ . $\beta=2.0$ is recommended for situations where the corrosion rates are higher.
		2.00	XS2 / XS3 ²⁾ XD2 / XD3 ²⁾	
Carbonation		1.50	XC1 – very dry XC3 – moderate humidity	
		2.00	XC2 – wet, rarely dry XC4 – cyclic, wet and dry	
Carbonation	500 years or total time	1.50	XC2 – wet, rarely dry XC4 – cyclic, wet and dry	Since lower corrosion rates are expected for XC1 and XC3, a lower reliability index of 0.5 is accepted at the end of the required integrity time. The reason is that, although the probability of depassivation is high, negligible corrosion rates are expected in dry to moderate humidity environments.
		0.50	XC1 – very dry XC3 – moderate humidity	
<p>1) Assuming that chlorides are a concern during surface storage only. It is not anticipated that chloride contaminated environment will be present in the GDF.</p> <p>2) These exposure classes are generally not experienced during surface storage.</p> <p>3) State that corresponds to conditions beyond which specified service requirements for a structure or structural element are no longer met.</p>				

4.3.5 Measures to minimise the risk of early age cracking

Concrete cracking during hardening is a common problem in concrete structures with high cementitious contents and low water-cement ratios, and is caused by temperature and autogenous shrinkage effects. This type of cracking is also known as “thermal cracking”.

Although the process of hardening is not fully understood, calculation methods exist to reduce the risk of thermal cracking in concrete. Hand calculation methods can be found in CIRIA C660 [48], but it is also possible to realistically simulate behaviour of the temperature, strength, stress and creep effects in concrete through the use of appropriate analysis software. Good practice indicates that the cracking risk is minimised if the thermally induced tensile stress, typically during the first seven days after placing, does not exceed 50%

of the concrete's tensile strength capacity. However, when crack formation is likely to occur, the following measures should be adopted:

- Material choices:
 - adopt cement combinations with low temperature rise properties, for example, adoption of fly ash or GGBS as partial cement replacement in sufficient quantities
 - avoid high cement contents as these produce more heat during hydration
 - avoid low water/cement ratios as these imply finer pore structure and high autogenous shrinkage
 - control the fresh concrete temperature during casting
- Measures on site/during construction:
 - cooling newly cast structures, for example, provision of cooling pipes
 - heat of adjacent structure
 - thermal insulation
 - change the construction phase to limit heat rise and reduce re-strain.

4.4 Cast iron

4.4.1 Introduction

Cast iron, typically in the form of DCI, has been utilised as a material for waste container construction, most notably within the German internal market. Cast irons possess a wide range of structures and properties, with the common factor that they are iron-carbon alloys with a carbon content of more than 1.7%, usually between 2% and 5%. Selection of the appropriate cast iron material grade is essential to ensure that the waste container meets the requirements defined by RWM.

To aid this selection, an initial overview of cast iron grades is provided below, which details the wide array of cast iron materials available to the designer. More detailed guidance is then provided for DCI, which is the material that has been utilised to date for the manufacture of waste containers, principally due to its mechanical properties and good manufacturability.

4.4.2 Overview of cast iron grades

Cast iron is similar to steel in matrix composition but it typically has a higher carbon and silicon content and includes an array of other alloying elements. Another difference is that, in steels, the carbon takes the form of carbide, whereas in cast iron the carbon commonly takes the form of graphite in various forms (other than in white or alloy white irons, where carbides are formed).

The properties of each cast iron grade are dependent upon the form of the graphite (or carbide) and the matrix structure. These are principally determined by the material composition, including trace elements, and the method of processing.

Cast iron grades may be classified into three main groups:

- White irons: non-alloy and alloy
- Malleable irons
- Graphitic irons: flake, ductile (spheroidal) and compacted.

All cast irons share the common trait of excellent casting properties due to the material's solidification characteristics. However, their properties vary significantly due to the resulting material structure. Of the three main groups above, it is the graphitic irons that are of most interest to the waste container designer. This typically leads to the utilisation of DCI as the most appropriate material for waste container construction. The difficulties presented by white irons and malleable irons are briefly described below.

White irons, when unalloyed, are typically hard and brittle in nature and have limited applications in high integrity environments. Alloyed white irons, although remaining brittle, can provide wear and abrasion resistant material depending upon the alloying element. However, costs and issues with processing capabilities also make them largely unsuitable for waste container applications.

The use of malleable irons is relatively limited, as strength and ductility combinations are often not optimal. Their use tends to be restricted to low cost, small, mass-produced parts such as pipe fittings. For the purpose of this guidance, they can be discounted with respect to high integrity applications such as waste container manufacture.

The group of most interest to waste container designers is therefore graphitic irons, a group which itself may be subdivided into three separate subgroups, namely:

- Flake – grey cast iron
- Compacted graphite iron (CGI)
- Ductile cast iron (DCI) – spheroidal.

Flake or grey cast irons are a large group of alloys characterised by a microstructure of graphitic flakes in a ferrous matrix. The materials are widely used in general engineering applications, with castings produced over a very wide range of masses. This form of cast iron is perhaps most familiar to an engineering designer and cast products can exhibit good dimensional stability, damping capacity, machinability and resistance to thermal shock. However, all grey cast irons are brittle, and fail in tension with minimal elongation. Therefore, for this principal reason, these grades are not suited to waste container applications which require demonstrable impact performance.

CGIs have improved strength and ductility when compared to flake graphite irons, and generally have better damping and thermal conductivity than DCIs. Recent developments in foundry technology have resulted in the use of these irons expanding due to these desirable properties. For example, the use of compacted graphite irons has become more widespread in the manufacture of large engine blocks, where the material's enhanced properties allow opportunities for reduced weight and package size in comparison to traditional materials such as grey cast iron or aluminium. However, although these grades exhibit good tensile strength, ductility is still minimal when compared to DCIs, which is likely to be detrimental to waste container impact performance. Therefore CGI grades are unlikely to be utilised for waste container applications.

The final group, DCI, provides the most practical interest to waste container designers. DCIs share a common trait in that the graphite is present in the form of spheroidal nodules rather than flakes which reduces the weakening effect of the graphite upon the matrix, and as a consequence these irons exhibit significantly enhanced strength and ductility when compared to flake irons. The production of DCIs requires a high degree of process control, particularly during the cooling phase, in order to produce the desired nodule size, form and count, all of which significantly affect the material performance. Note that the principal properties of concern to the waste container designer, namely relating to strength and ductility, decrease as the proportion of non-nodular graphite increases.

DCIs have a range of properties largely controlled by the matrix, which can range from completely ferritic to pearlitic (as cast or normalised during post-cast heat treatment). Pearlitic grades are characterised by high strength, and relatively low ductility; therefore waste containers produced from this material may not exhibit the required performance in impact. In contrast, ferritic grades exhibit lower tensile strength but good ductility, with an associated improvement in the impact performance of waste containers utilising this material.

In waste container design, it is highly likely that the requirements will necessitate that the material provides the waste container with good impact performance; therefore, in practice, ferritic grades are often the most suitable as a high percentage elongation is highly desirable to prevent material failure. This balance between tensile strength and ductility is best evaluated by detailed investigation of the elastic-plastic strain dependent behaviour of the material under impact using finite element analysis.

There are a number of DCI subgroups, which may be of interest to the waste container designer, such as austempered ductile iron (ADI) and austenitic alloyed grades. ADI grades are subjected to a specialised iso-thermal (austempering) process which transforms the matrix structure and can produce exceptional strength, ductility and wear resistance. Austenitic alloyed grades are usually high nickel-containing irons developed to provide good creep and oxidation resistance combined with a high resistance to corrosive environments. The properties of ADI and austenitic grades certainly merit consideration from the waste container designer, although, the higher processing costs, complexity and limited commercial availability when compared to ferritic DCI grades presently limit this consideration to more specialised applications.

4.4.3 Desired material properties for waste container applications

The conclusion from the outline of cast iron grades above, is that the designer is recommended to select a ferritic DCI grade to manufacture their waste container. Specific areas of material properties that need to be further considered in selecting a suitable grade are described below, and it is recommended that advice be sought from Suitably Qualified and Experienced Persons (SQEPs) in metallurgy and/or casting, to ensure that an appropriate grade is specified to meet the design requirements.

Tensile strength

It is highly desirable to utilise a material with good tensile strength for the manufacture of waste containers. For example, the waste container's lifting features and their surrounding material will almost inevitably experience tensile stresses. Lifting features are utilised routinely during waste container operation, and therefore acceptance

criteria typically require that the stresses due to lifting are within the material's elastic limit. DCI can be specified with a range of tensile strengths (typically 350 MPa to 900 MPa) and associated proof stresses (typically 220 MPa to 600 MPa). The range of tensile strengths available provide flexibility to the waste container designer in the lifting feature design. However, as previously noted, as the tensile strength increases, the ductility (percentage elongation to failure) of the material decreases, which adversely affects impact performance. Therefore inevitably the designer will have to balance the desired tensile strength against the waste container impact performance and select an appropriate grade that satisfies both criteria. This is likely to be a grade towards the lower end of the DCI material tensile strengths as these grades have the higher elongation to failure.

Compressive strength

DCIs, in common with most iron grades, exhibit good compressive strength. Practically, proof strengths can be assumed to be typically from 220 MPa to 600 MPa depending upon the selected grade. Test data has shown that in actuality the 0.2% compressive yield strength can be up to 20% higher than the tensile yield strength. As explained previously with regards to tensile strength, in practice, a compressive strength towards the lower end of this range will most likely be utilised due to the need for a material with a higher elongation to failure to achieve the waste container's desired impact performance.

Elongation to failure

Good elongation to failure is highly desirable in a material for waste containers in order to achieve the required impact performance. Elongation to failure varies typically between 2% and 22% over the range of DCI grades. When grades with higher elongation to failure are specified, the material is seen to undergo "solid metal flow" during impact where the material displaces under plastic strain, converting the impact energy into strain energy. Critically, the material does not fracture prematurely. As the elongation to failure lowers, the DCI material becomes harder, less tough, and more brittle in behaviour, although as noted above the tensile and yield strength of the material increases.

As with most materials, material properties of DCI vary with strain rate. Although the initial selection of material grades could be based on elongation to failure from static tests, variation of material properties with strain rates, up to the strain rates that the material of a waste container would experience in an impact event, should be characterised by tests and used in any finite element analyses that are used to demonstrate the waste container's impact performance.

It should also be noted that the failure behaviour is sensitive to triaxiality.⁵

The thick walled nature of most DCI containers makes this a prominent feature of its material behaviour. Variation of failure with triaxiality should be characterised by tests.

⁵ Triaxiality is a measure of the three-dimensional stress state, to determine whether it is uniaxial, biaxial or triaxial, and is defined as the ratio of mean stress to Von Mises stress.

Fracture toughness

Fracture toughness is a property which describes the ability of a material containing a crack to resist fracture. Fracture toughness is a quantitative way of expressing a material's resistance to brittle fracture when a crack or other defect is present. If a material has a high fracture toughness, it will most likely exhibit ductile fracture, whereas a low fracture toughness will most likely lead to brittle fracture.

DCI, when appropriately specified, can be considered to have good fracture toughness. DCIs share a common trait in that the graphite is present in the form of spheroidal nodules rather than flakes, which reduces the weakening effect of the graphite upon the matrix. With regard to fracture toughness, these spheroidal nodules are seen to arrest crack propagation, and as a consequence these irons tend to exhibit ductile rather than brittle behaviour.

Various studies have evaluated the relationship between fracture toughness and physical material properties in DCI [49]. These studies have shown that there is a good linear correlation between graphite nodule spacing and fracture toughness. Further studies have shown that graphite size and shape are also important considerations, as well as the percentage of pearlite in the metal matrix.

In practice, to maximise material fracture toughness, a waste container material specification should seek to specify a DCI grade with low percentage of pearlite, highly spherical nodules and high nodule count. Further guidance upon these aspects of material specification can be found in ASTM A874 [50].

Thermal behaviour

As discussed above with regard to impact performance of the waste container, ductile irons are structurally stable at very low temperatures, but when designing for low temperature applications, the designer must take into consideration the significant effect of temperature on strength, elongation and fracture toughness. Ferritic grades of ductile iron are generally preferred for low temperature applications because their ductility at low temperatures is superior to that of pearlitic grades. This ductility at low temperature in ferritic grades is manifested in a lower ductile-to-brittle transition temperature than pearlite grades.

At the other end of the operating spectrum, DCIs exhibit several properties which enable them to perform successfully in numerous elevated temperature applications. Unalloyed grades retain their strength to moderate temperatures and exhibit significantly better resistance to growth and oxidation than unalloyed grey iron. Alloyed DCIs, particularly austenitic alloyed grades, can provide excellent resistance to deformation, growth and oxidation at high temperatures.

The only high temperature applications in which DCIs do not perform well are those involving severe thermal cycling. In these applications, the low thermal conductivity of ductile iron combined with a high modulus of elasticity can result in internal stresses high enough to produce cracking and warping. However, this is unlikely to be a major consideration for a waste container designer, as high temperature applications are generally limited to the consideration of accident conditions, which by definition cannot be considered as frequent occurrences.

Practically, for operating temperatures up to 300°C, static design stresses can be based upon the room temperature yield strength. This is likely to cover any perceived operating conditions. If accident conditions require further consideration for temperatures above 350°C, design stresses should be related to creep data for applications in which dimensional accuracy is critical, or stress rupture data when deformation can be tolerated but time to failure is critical.

With regards to oxidation, ferritic DCIs are stable up to a critical temperature of approximately 730°C. In either a transport or disposal fire accident scenario, the temperature experienced by the waste container would exceed this critical temperature for a relatively short duration, although the short duration means that oxidation is unlikely to be of major concern for thick-walled waste containers.

It should be noted that material properties of DCI vary with temperature. The properties quoted in material standards are typically room temperature properties, and assume that the material is acting in a ductile manner. At lower temperatures, DCI goes through a ductile to brittle transition, whereby the properties change to a more brittle nature. This temperature, the ductile to brittle transition temperature, can vary due to many metallurgical factors, particularly the percentage of alloying elements, grain size, grain form, graphitic nodule size and nodule form. The designer should select a material grade that has a ductile to brittle transition temperature lying outside the required service temperature range defined by RWM.

To accurately evaluate the ductile to brittle fracture transition, it is recommended that temperature variations across the intended operating range are included in the high strain rate testing discussed above.

Corrosion resistance

Unalloyed DCIs exhibit approximately the same corrosion resistance as grey iron, and are superior to unalloyed steel, and even highly alloyed steel in certain environments. Corrosion of ductile irons is a complex phenomenon and a detailed discussion of corrosive behaviour is beyond the scope of this guide.

Practically, a waste container designer would need to understand expected material loss during the postulated waste container lifetime. Studies have shown that in benign storage environments, a bounding material loss of 10 µm/year can be assumed on unprotected DCI surfaces [51]. Consideration may be given to inclusion of a corrosion allowance in the waste container wall thickness to allow for expected through life surface deterioration, although it may be possible to demonstrate that such reduction does not produce an unacceptable reduction in container performance, recognising that an advantage of thick-walled cast iron is that corrosion is uniform, predictable and unlikely to have a significant effect upon the performance of the waste container.

If enhanced corrosion resistance is considered a requirement, then austenitic alloyed grades containing relatively high nickel content may be considered, as their corrosion performance is significantly improved upon the unalloyed material.

4.4.4 Material standards

The most applicable standard for the selection of the exact material grade is ISO 1083:2004 Spheroidal Graphite Cast Irons – Classification [52]. This standard defines the grades and the corresponding requirements for spheroidal graphite cast irons. It specifies a classification based on a combination of tensile stress, proof stress and percentage elongation, or alternatively as a function of hardness. In practice the specification of the material by stress and percentage elongation is likely to be more useful to the waste container designer. For example material grade ISO 1083/JS/350-22 is a DCI with a minimum tensile strength of 350 MPa and an elongation of at least 22%.

Note that this standard does not specify other material elements, such as chemical composition, which will vary depending upon the exact method of manufacturing and therefore needs to be established in consultation with the chosen foundry. Often the exact chemical composition will be the foundry's proprietary information, and the material acceptance is therefore largely based upon consistency of mechanical properties. Guidance on expected chemical composition is provided within numerous references, for example see [53] and [54].

Furthermore, as explained above, the properties of the DCI are largely dependent upon the form, size and count of spheroidal graphite nodules in the matrix. Therefore in order to ensure the desired material performance these properties will also have to be defined to the foundry as part of a material specification. Further guidance upon items such as the form, size, and count of the nodules can be found within ASTM A874/A874M Standard Specification for Ferritic Ductile Iron Castings Suitable for Low-temperature Service [49].

5. Designing a waste container to meet the requirements for waste packages for the packaging of LHGW

5.1 Introduction

The sub-sections in this section generally follow the structure of Section 3 of the Waste Container Specification [4]. Table 4 gives the corresponding sub-section of Section 3 of the Waste Container Specification to each sub-section of Section 5 of the present document.

Table 4: Corresponding sub-sections of Section 3 of the Waste Container Specification and Section 5 of this document

Waste Container Guidance (This Document)		Waste Container Specification (WPS/430)	
Heading number	Heading title	Heading number	Heading title
5.2	External dimensions	3.1	External dimensions
5.3	Handling features	3.2	Handling features
5.4	Stackability	3.3	Stackability
5.5	Identification	3.4	Identification
5.6	Durability of waste container integrity	3.5	Durability of waste container integrity
5.7	Filling performance	–	–
5.8	Maximum gross mass	3.6.1	Maximum gross mass
5.9	External dose rate	3.6.2	External dose rate
5.10	Heat output	3.6.3	Heat output
5.11	Surface contamination	3.6.4	Surface contamination
5.12	Gas generation	3.6.5	Gas generation
5.13	Criticality safety	3.6.6	Criticality safety
5.14	Impact performance	3.6.7	Accident performance
5.15	Thermal performance	3.6.7	Accident performance

The discussions in each of the sub-sections are generic where possible, but focus on the different types of waste containers giving “type-specific” guidance where appropriate, for example, reinforced concrete containers, DCI containers and stainless steel containers. Examples of good practice from existing waste container designs are also included where appropriate and available.

5.2 External dimensions

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

Waste packages could be transported to the GDF by road, rail, sea or inland waterway, or by a combination of these means. As set out in the NDA Transport and Logistics Topic Strategy [55], there is a preference to use rail over road where practicable, although in general, transport by rail is the most restrictive in respect of transport package external dimensions.

For transport by rail, the maximum overall dimensions of a transport package, including any external frame or overpack, are set by the need to be compliant with the relevant ‘loading gauge’. To permit the use of a large proportion of the UK rail network, the Generic Transport System design (GTSD) [56] uses the W6a loading gauge [57] as the basis for defining the maximum overall envelope. The maximum width and height of a cuboid transport package are therefore assumed to be approximately 2.438 m and 2.591 m respectively, based upon the dimensions of a standard ISO freight container.

It should be noted that the loading gauge is not rectangular, that space may be needed for protective covers, and that the precise envelope will depend upon the rail wagon design, taking account of the deck height, bogie centres and overhang, and suspension movement.

Restrictions will also exist for the length of transport packages; whilst these are less onerous than those on height or width, length increases can increase overhang and consequently reduce the available width or height. Larger waste packages could also be transported by road, subject to the limits in the Road Vehicle (Construction and Use) Regulations [58] for special vehicle types.

It is worth reiterating that the dimensional constraints imposed by the transport system apply to the transport package. These limits are therefore directly relevant to the design of the waste containers that are intended to be transport packages in their own right. Where the waste package will be transported inside a transport container, the design of the waste container needs to be compatible with the internal cavity of the identified transport container.

For example, the standardised designs of unshielded waste packages will be transported using the Standard Waste Transport Containers (SWTC), the designs of which incorporate sufficient shielding to allow for the safe transport of unshielded waste packages. In this case, the external dimensions of the waste package are therefore constrained by the SWTC cavity dimensions, as indicated in Table 5.

Table 5: Maximum external dimensions of unshielded waste packages transportable in the different SWTC variants

SWTC Variant	Shielding thickness	Maximum dimensions of waste package transported (length × width × height)	Waste package types
SWTC-70	70 mm	1.72 m × 1.72 m × 1.25 m	Four 500 litre drums in a stillage
SWTC-285	285 mm		3 cubic metre box variants 3 cubic metre drum
SWTC-150	150 mm	1.85 m × 1.85 m × 1.37 m	Miscellaneous Beta Gamma Waste Store (MBGWS) box

The most restrictive handling process in respect of transport package external dimensions in the current generic designs for a GDF, as defined in the Generic Disposal Facility Designs (GDFD) report [59], is transfer of the packages underground by drift or shaft:

- Drift transfer is assumed to use rack and pinion railway with dimensional limits equal to those for offsite rail transport.
- Shaft transfer is by a shaft winder and cage with a 9 m diameter shaft. This limits the maximum package length and width to approximately 7.3 m and 3.0 m, respectively.

Specific dimensional envelopes for the standardised designs of waste containers are defined in the relevant WPS; these take into account the constraints relating to transport and GDF operation. In designing waste containers to the external dimensional envelopes specified in the WPS, it should be noted that:

- The external dimensional envelopes are the external dimensional envelope of completed waste packages and not of empty waste containers. Therefore, deflection of the waste container due to filling (including any waste loading, grouting, in-container waste treatment, mixing), must not cause the dimensions to exceed the external dimensional envelope.
- The external dimensional envelopes are defined to facilitate transport to the GDF, emplacement in the GDF and handling in the GDF over the operational period of the GDF. Therefore, any change in dimensions prior to transport to the GDF and over the operational period of the GDF must be considered to ensure that the external dimensional envelope is not exceeded.

5.3 Handling features

Lifting features, lifting load and performance criteria for individual waste package types are defined in their respective WPS.

There is a requirement for tiedown of transport packages during transport. This applies directly to the 2 metre box, 4 metre box and 6 cubic metre concrete box. In the case of waste packages transported in a transport container, there is a need for restraint to comply with limits on changes to external dose rate and so that the transport package or waste package's ability to meet other limits on its performance is not impaired. This need is usually met through the use of close fitting guides or frames, such as a stillage, rather than through using dedicated tie-down features.

The geometry and location of twistlock fittings for tiedown for the 2 metre box, 4 metre box and 6 cubic metre concrete box are defined in the relevant WPSs. Such packages should be designed to satisfy the tie-down requirements of TCSC 1006 [60] for the maximum mass of the package as specified in the WPS.

To permit the safe and efficient handling of waste packages, all waste containers are required to incorporate handling features according to their type as defined in their respective WPS and compatible with the handling systems that are currently assumed in RWM's generic transport system and GDF designs. Lifting grabs and lifting frames for the standardised waste packages are defined in WPSs as shown in Table 6 below:

Table 6: WPSs of lifting grabs and lifting frames for the standardised waste packages

Package type	WPS of lifting grab or lifting frame
500 litre drum	WPS/600
3 cubic metre box – corner lifting variant	WPS/604
3 cubic metre box – side lifting variant	WPS/601
3 cubic metre drum	WPS/601
Miscellaneous Beta Gamma Waste Store (MBGWS) box	not specified
2 metre box	WPS/603
4 metre box	WPS/602
6 cubic metre concrete box	not specified
500 litre concrete drum	not specified
1 cubic metre concrete drum	not specified
500 litre robust shielded drum	not specified
3 cubic metre robust shielded box	not specified

In terms of loading, the WPSs specify that packages shall incorporate lifting features which enable the waste package to be lifted with a load equal to twice the weight of the waste package. This factor of two on the weight of the waste package is termed the “snatch factor” and is intended to take account of the dynamic amplification of the load during lift. The WPSs also specify that for waste packages that have four lifting points, they shall be capable of being lifted using two diagonally opposite lifting points. This is intended to cover the situation where one lifting point is inactive, for example, due to out-of-flatness between the lifting surfaces of the lifting features.

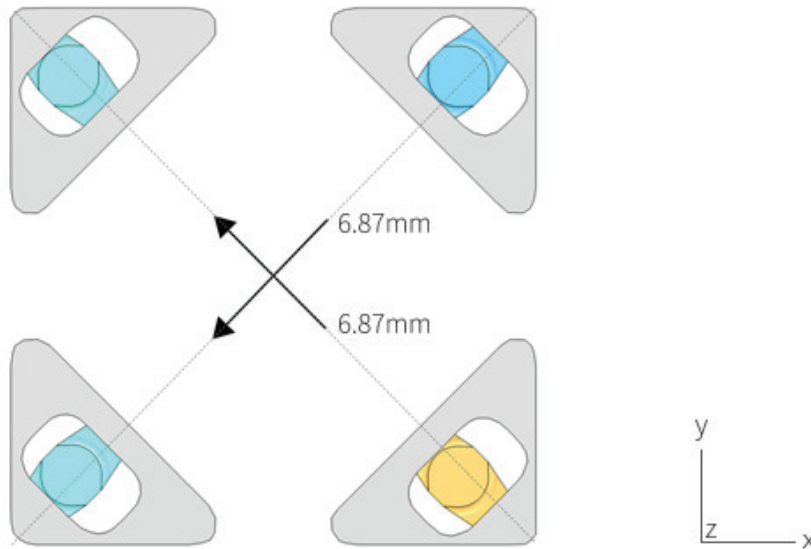
In terms of performance criteria, the WPS states that the waste package must not “*exhibit any permanent deformation or abnormality that would render it incompatible with any of the requirements defined in the WPS*”. It should be noted that this is not just a requirement on the lifting feature but a requirement on the waste container as a whole. The behaviour of the whole waste container must be considered. The load path from the load due to the wasteform and the waste container, through the waste container structure, to the lifting features, should be understood.

In designing a waste container to satisfy the lifting requirements specified by RWM, the following should also be taken into account:

- The geometry of the lifting feature of the handling systems: The geometry of the twistlocks (as defined in WPS/601 to WPS/604) for box type packages and the geometry of lifting grabs (as defined in WPS/600) for 500 litre drum packages, should be taken into account when designing waste containers for lifting. This is so that the geometry of the interface between the lifting feature of the handling system and the lifting feature of the waste container, and hence the bearing area for the transfer of the lifting load, can be correctly taken into account in the design.
- Off-set of the lifting feature of the handling system with respect to the lifting feature of the waste containers: In order to facilitate engagement of the lifting feature of the handling system with the lifting feature of waste packages, there will be clearance between the lifting feature of the handling system and the lifting feature of the waste package when they are engaged.

For example, a box may not be perfectly aligned centrally within the lifting frame, and hence the twistlocks will be offset in the twistlock apertures. This is illustrated in Figure 2 below by way of the possible position of the twistlocks in the twistlock apertures of the RWM reference stillage. Such variation in engagement position could have a significant effect on the stresses in the twistlock aperture and the adjacent structure.

Figure 2: Illustration of “float” of the twistlock stems against the twistlock apertures, using the RWM reference stillage as an example



- Variation in geometry and material properties due to ageing over the design life timescale: Degradation of the waste container (for example, thinning of steel section due to corrosion, cracking of concrete) over the design life timescale required by the WPS must be taken into account when designing for lifting. Justification must be provided of any degradation mechanism assumed in the design.

The design of the lifting system should take account of manufacturing processes and tolerances of waste containers so that the lack of flatness at the interface can be accommodated in the design. It should also be designed such that deflections due to the filling process can be accommodated.

Variation in geometry and material properties of the waste container (for example, thinning of steel section due to corrosion, cracking of concrete) over the design lifespan due to ageing must be used in the lifting design. For example, lifting behaviour should be analysed using the thinned plate thicknesses after taking into account corrosion, rather than assuming the plate thicknesses of a new waste container. Justification must be provided of any degradation mechanism assumed in the design.

It is good practice to design the lifting performance of the waste container to recognised structural codes of practice. An example of a suitable design code and design criteria for designing a reinforced concrete package, which has twistlock fittings for handling, to satisfy the lifting requirements is as follows:

- The stresses in the twistlock assemblies including the twistlock pockets and the tie-bars which connect the twistlock pockets to the reinforced concrete structure are to be checked against the “basic stress” limits of BS 2573 [61]:
 - for axial tension, the stress shall not exceed $0.6 Y_s$ where Y_s is the yield stress of steel
 - for compression, the stress shall not exceed $0.6 Y_s$
 - for bending, the stress shall not exceed $0.65 Y_s$
 - for bearing, the stress shall not exceed $0.8 Y_s$.
- Stresses in the concrete are to be assessed against Eurocode 2 (BS EN 1992)

1:2004) [22]:

- in axial compression or flexure, stress shall not exceed $0.85f_{ck}/1.5$, where f_{ck} is the characteristic compressive strength of concrete
 - in bearing, $1.0f_{ck}/1.5$.
- Stresses in the reinforcement are to be assessed against Eurocode 2 (BS EN 1992-1-1:2004) [22]:
- stresses in the reinforcement should not exceed $f_{yk}/1.0$, where f_{yk} is the yield stress of the reinforcement steel.

In addition, permanent crack size in the concrete due to the loading should be assessed against a crack size limit. A crack size limit should be determined considering the nature of the wasteform and the expected size of particulates in the wasteform. It should be small enough so that the containment function of the waste container will not be compromised with the presence of cracks which are within the limit.

An example of the design code and criteria for designing a stainless steel waste container to satisfy the lifting requirements for an unshielded waste package is as follows:

- It is to be designed to the requirements of BS 2573-1:1983 [60]
- The following basic stress limits (where Y_s is the 0.2% proof (yield) stress of the steel) should be satisfied:
 - elements subject to simple axial tension $P_{at.bas} = 0.6 Y_s$
 - plate elements subject to bending $P_{bt.bas} = 0.65 Y_s$
 - members subject to bearing $P_{b.bas} = 0.8 Y_s$
 - members subject to shear $P_{q.bas} = 0.37 Y_s$
 - members subject to compression A_s per section 5.1.4.2 of BS 2573
 - for elements subject to a combination of stresses the members will be proportioned in accordance with the requirements of clause 5.1.7 to BS 2573
- In addition, any deflection limit (for example, to satisfy any operation requirement) should be defined and satisfied.

5.4 Stackability

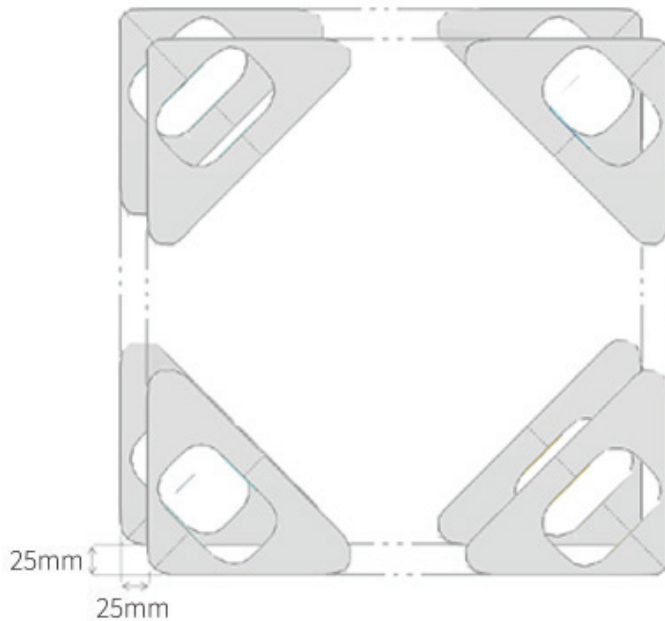
The stacking requirements for each waste package type, including the maximum stacking height in the GDF, are defined in their respective WPS. With the exception of 500 litre drums, which will be transported and disposed of in four-drum stillages, all waste packages are required to rely on their own design to withstand stacking loads, that is, the load when stacked within a stack of waste packages of the same design at their maximum gross mass.

Each package is required not to suffer any permanent deformation or abnormality that would render it incompatible with any of the other requirements defined in the WPS. That is, after being stacked, it must maintain its ability to be handled safely, its dimensions must remain in conformance with the dimensional envelope defined in the WPS, its handling features must remain in conformance with those defined in the WPS, and it must be capable of being lifted in accordance with the lifting requirement in the WPS.

In order to cater for potential misalignment of packages when stacked in the GDF, waste containers must be designed for two alignment scenarios:

- In-line stacking – stacking with all the packages in a stack fully aligned.
- Off set stacking – stacking with the packages above the bottom package aligned with each other but off-set from the bottom package. For all box-type packages, the off-set shall be 25 mm in each orthogonal direction in plan, as illustrated in Figure 3 below. For drum-type packages, the off-set shall be 25 mm in a radial direction in plan.

Figure 3: Illustration of off-set for box type packages



In these two scenarios, the geometric details at the interface between adjacent waste containers would be different. Hence the load path between adjacent waste containers and the resulting stresses in the waste containers would be different. Therefore, waste containers need to be designed for both scenarios.

Variation in geometry and material properties of the waste container (for example, thinning of steel section due to corrosion, cracking of concrete) over the design lifespan must be taken into account when designing for stacking. Justification must be provided of any degradation mechanism assumed in the design.

Due to the manufacturing tolerances and deflections of the waste containers during filling (see Section 5.7), the interfaces with the waste package above it and below it may not always be perfectly flat. The waste container should be designed such that the resulting unevenness in the distribution of load can be tolerated.

When designing waste containers to satisfy RWM's stacking performance, the floor on which the packages are stacked can be assumed to be flat, horizontal and non-deformable.

The base of waste packages should ideally not have protruding features, for example, feet, in order to avoid concentration of load on the vault floor of the GDF.

Waste containers should be designed such that when they are stacked, the vents are not obstructed.

It is good practice to rely only on the waste container structure rather than the wasteform to carry the stacking load. While the waste container structure can be designed for long-term loading performance, the wasteform is not primarily intended for structural load carrying purpose, and to do so is to add to the many other criteria it already has to satisfy. If a package has to rely on the wasteform to carry the stacking load, the following must be ascertained:

- The load carrying capacity of the wasteform
- The long-term integrity of the wasteform
- The integrity of the interface between the wasteform and the waste container that lies within the load path of the stacking load.

Waste containers manufactured from thin steel sections typically carry the stacking load by using stacking posts, which are essentially columns formed by bending of the waste container wall or welding of additional plates to the wall to increase its stiffness, in order to carry the load without buckling. Typically, the twistlock aperture plate would stand proud of the top of the waste container to channel the stacking load into the stacking post. For waste containers with a thick wall, the stacking load is typically carried by the wall of the waste container without requiring a specific “stacking post”, as the walls are typically substantial enough to carry the load without buckling.

If dedicated stacking posts are to be incorporated in the design, both open and closed sections are acceptable from a structural point of view, provided they are designed adequately. However, in selecting the structural form for the stacking post, the RWM requirements to facilitate decontamination and to minimise voidage when the GDF is ultimately backfilled must also be taken into account. The generic design of the side-lifting variant of the 3 cubic metre box satisfies these requirements by having stacking posts that are channels which open towards the outside. The RWM reference stillage satisfies these requirements by having bleed holes incorporated into “closed-section” stacking posts. They are illustrated in Figure 4 and Figure 5 below.

Figure 4: Illustration of an “open” stacking post, as used in some designs of 3 cubic metre box

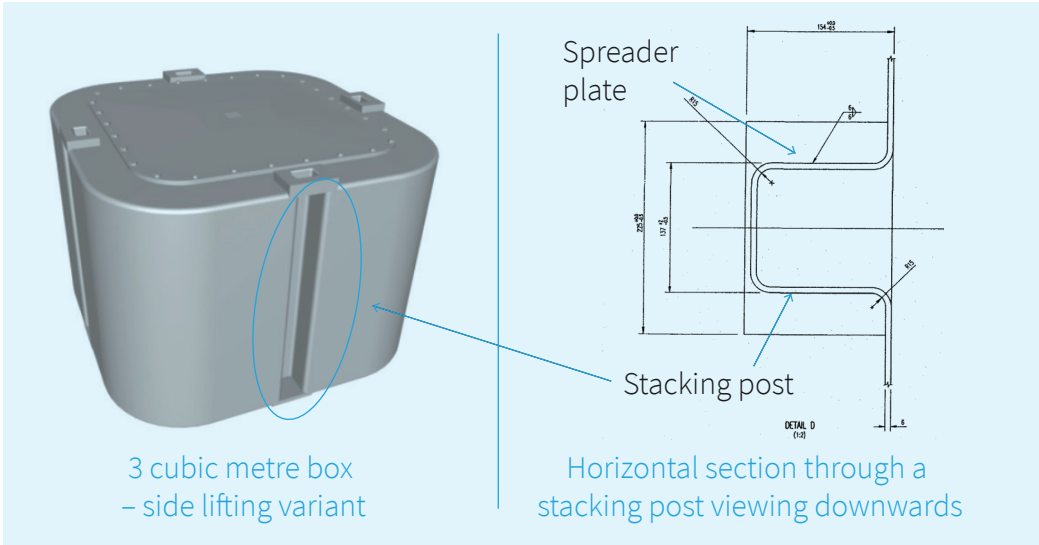
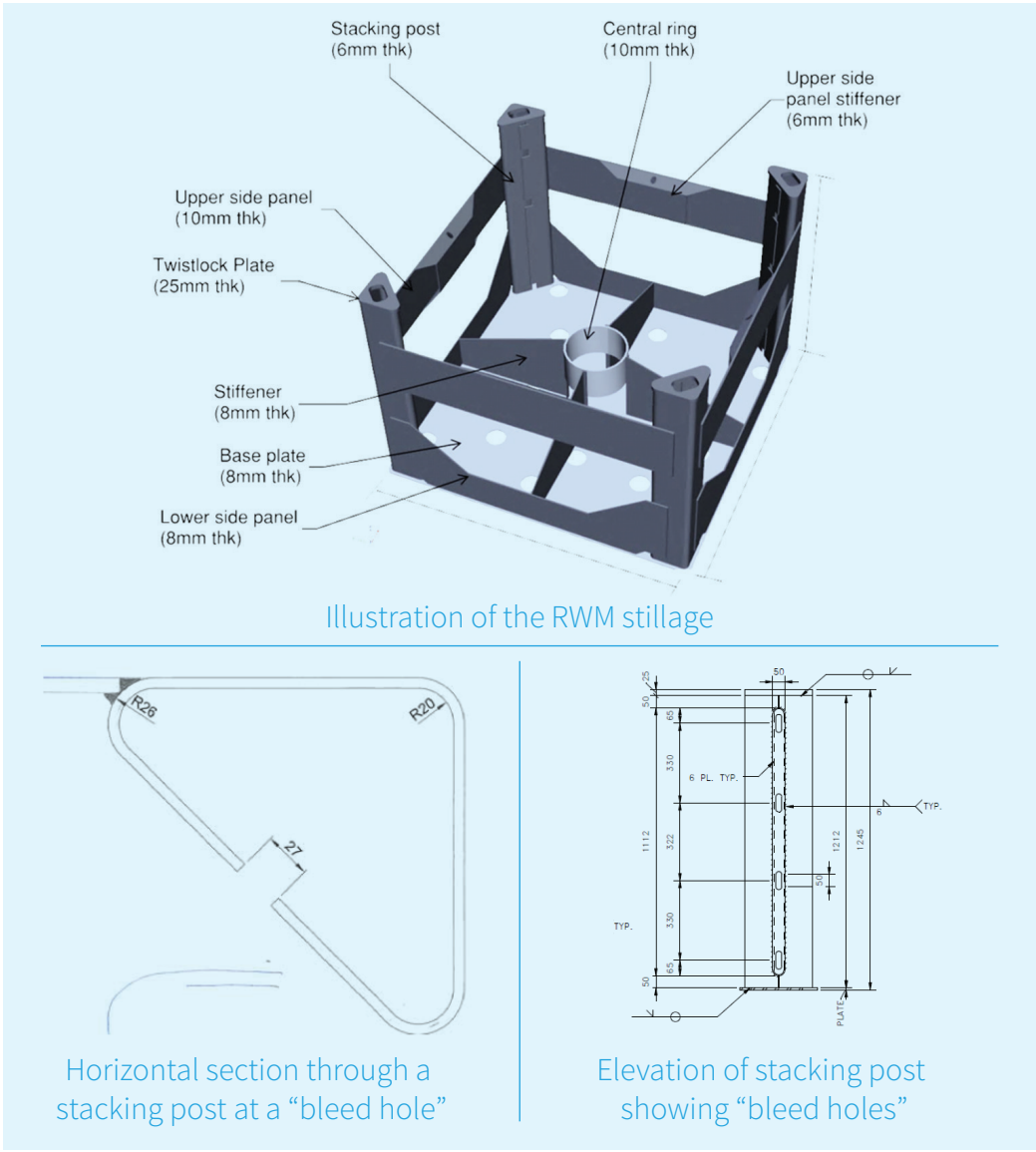


Figure 5: Illustration of a “closed section” stacking post, using the stacking posts of the RWM stillage as an example



It is good practice to design the stacking performance of the waste container to a recognised structural code of practice. Stainless steel containers could be designed to the requirements of BS EN 1993-1-4 [62], with the loading as defined in Eurocode – Basis of Structural Design [46]. The self-weight of the package and the stacking load on the package should be conservatively treated as Variable Loads. The performance of the waste container should be demonstrated against ultimate limit state⁶ requirements of the code for strength and stability, and against serviceability limit state⁷ requirements of the code for deflection. The partial factor for materials will be 1.1 in accordance with clause 5.1 (2) applied to the yield strength f_y (or 0.2% proof stress in the case of stainless steels). The partial factor for loads will be taken as 1.5 for a leading variable action as table Na.A1.2 (A) of the UK National Annex for Eurocode – Basis of Structural Design [63]. Similarly, reinforced concrete containers could be designed to the requirements of BS EN 1992.

5.5 Identification

Location and dimensional details of the identifiers for the different standardised waste package types are defined in their respective WPS.

Waste package identifiers will need to remain machine readable for a period that permits identification of the waste package at least until the vault is sealed, that is, a minimum period of 150 years after the waste package is manufactured.

The recommended method of inscribing identifiers on stainless steel waste containers is to laser etch the characters, a method that is expected to satisfy the requirement specified for the longevity of the marking. The identifiers could be laser etched directly to the structure of such waste containers or they could be applied to stainless steel identification plates which are then attached to the waste container at the required locations. For waste container material that is thinner than about 5 mm, laser etching should not be applied directly to the waste container.

The laser etching should be of sufficient contrast to facilitate remote reading techniques. The surface surrounding the laser etching should be of a matt finish to improve the contrast with the laser engraving to facilitate remote reading.

Identification plates should be attached securely so that they remain attached to the waste container for the required period (that is, 150 years). The method of attachment should not compromise the performance of the waste container in other areas of performance.

6 Ultimate limit states are concerned with the safety of people and the structure. Examples of ultimate limit states include loss of equilibrium, excessive deformation, rupture, loss of stability, transformation of the structure into a mechanism, and fatigue.

7 Serviceability limit states are concerned with the functioning of the structure under normal use, the comfort of people, and the appearance of the construction works. Serviceability limit states may be reversible (e.g. deflection) or irreversible (e.g. yield).

In the case of DCI waste containers, the surfaces of which are painted, the identifiers should be laser etched onto stainless steel identification plates as described above, which are then attached to the waste container at the required locations by bolts. The designer should ensure that the specified spacing, depth and diameter of the bolt holes do not compromise the waste container's integrity.

For reinforced concrete waste containers, the identification plates could be attached to the reinforcement bars, or provided with embedment tails, and cast-in with the concrete. If attaching to reinforcement, due consideration should be taken of bimetallic corrosion.

There may be alternative methods of inscribing identifiers which satisfy the stated requirements. The adequacy of such methods should be demonstrated if they are to be employed.

5.6 Durability of waste container integrity

5.6.1 Long-term integrity

The integrity of the waste container shall be maintained for a period of 150 years and should be maintained for a period of 500 years following manufacture of the waste package.

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

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

Atmospheric corrosion is a major potential threat to the integrity of a waste container. Other mechanisms of degradation include biodegradation, abrasion, radiolysis and chemical reactions between the waste container and its contents.

When selecting a material for the fabrication of waste containers, the designer will need to understand both the internal and external environments that a waste container will be subjected to, and determine which degradation mechanisms can take place in those environments.

The internal surfaces of waste containers will also be subjected to a range of conditions. The environmental conditions to which they will be exposed will be determined by both the waste and the conditioning process (in particular any encapsulating medium) and the physical/chemical properties of the resulting wasteform. This could involve conditions that may be physically and chemically aggressive, particularly in terms of low or high pH, oxidising/reducing conditions and temperature. These conditions may be short-lived when compared to the timescales associated with the required integrity lifetime of the waste container but they may nevertheless have longer-term detrimental consequences.

Radiolysis, that is the physical and/or chemical alteration of material exposed to ionising radiation, can result in the production of aggressive chemicals from materials in the wastefrom that accelerate degradation processes (such as hydrochloric acid from the radiolysis of polyvinyl chloride). Radiolysis may also result in a number of physical degradation effects including dimensional changes or cracking and spalling of concrete, and may be accompanied by gas evolution. The effects of radiolysis tend to be lowest in metals and alloys and greatest in polymer materials, with cementitious materials being intermediate in their response.

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.

Studies to quantify the degradation mechanism of different standard materials used in the manufacture of waste containers have been carried out by the industry and a summary of the information is presented in [50].

5.6.2 Integrity during transport

During normal condition transport operations, packages will be subjected to shock and vibrations.

While it is unlikely that the integrity of waste packages and waste containers will be affected, it would depend on the specifics of individual waste container design. All bolts should be tightened to an appropriate torque such that they will not be loosened due to the vibrations. Reinforced concrete containers should be designed such that when they are transported empty, for example, from the manufacturer's site to the waste packaging site, no cracking will occur due to flexing of the structure due to vibrations and shock.

5.7 Filling performance

'Filling' is defined as the processes used to create a wastefrom in the waste container. This could include waste loading, in-container waste conditioning, encapsulation, capping and mixing. Container furniture (for example, in-drum mixing devices, dewatering tubes, liners, anti-flotation plate) is often employed to facilitate the filling process to achieve the required wastefrom.

Waste containers should be designed such that permanent deformation due to filling is minimised.

The waste container should be designed such that the filled waste container does not exceed the required external dimensional envelope limit of the waste package. Deflections and stresses in the waste container due to filling should be understood and they should be taken into account in the lifting and stacking design of the waste container.

In assessing the behaviour of a waste container during filling, both the dynamic loading (for example, due to waste dropped into a waste container, especially into an inner container or inner liner) and static loading (for example, hydrostatic pressure due to wet grout on the waste container wall) need to be considered. The loading during the whole filling process, including waste loading, in-container waste treatment, waste encapsulation, mixing, etc., should be considered.

If a waste package is to be lifted or stacked before the grout is set, or after the waste is loaded but before it is encapsulated, the waste container should be designed to cope with the loading during handling and stacking during such intermediate states. While it is satisfactory to consider the lifting load or stacking load as static for completed waste packages, it may not be adequate for waste packages in these intermediate states for which the dynamics of the behaviour may also be significant and should be considered.

Typically, stresses and deflections in reinforced concrete containers and DCI containers during filling are trivial, due to the thick section of these waste containers.

Typical strategies to improve the stiffness of thin walled waste containers in order to reduce deflection during filling include welding stiffeners at strategic locations to the inside surfaces of the waste container, increasing the thickness of certain components (for example, body flange), and adding rolling rings or pressed ribs to the walls.

5.8 Maximum gross mass

The mass of the waste container shall be such that, together with the mass of the wasteform, the mass of the waste package complies with the maximum gross mass limit of the waste package defined in the WPS. Although there is no specific mass limit for waste containers, this requirement means that the mass of a waste container must not exceed the maximum gross mass limit of the waste package.

As the mass of a waste package is the sum of the mass of the waste container and the wasteform, a lighter container will allow a heavier wasteform. However, it is noted that the structure, and hence the mass, of a waste container is often driven by dimensional, stacking, lifting, impact, containment, durability, shielding and manufacturing requirements, and it may not be feasible to reduce the mass significantly without affecting the performance margin in other areas.

5.9 External dose rate

The waste container, in combination with the encapsulation medium, internal furniture and the waste itself where appropriate, shall provide adequate radiation shielding to ensure that the external dose rate of the waste package does not exceed the limits specified in the relevant WPS.

For unshielded waste containers and others that are transported in a transport container these dose rates are specified at the outer surface of the transport container. In the case of the SWTC, the choice of wall thickness of the SWTC will take dose rate into consideration as appropriate. Nevertheless, RWM's assessment process considers dose rate from the unshielded package and exceptionally this could be determined to require a limit on the radionuclide content.

For robust shielded waste packages and reinforced concrete shielded waste packages, the thickness of the container is typically chosen to provide the required level of shielding. For these containers, interfaces between removable components (for example, the interface between the lid and the body), and the interface between vent valve plug and the lid should be designed to minimise the shine path such that external dose rate limits are not breached. Typically, this is achieved by a stepped interface.

For shielded containers based on thin steel containers, the required amount of shielding is typically added to the inside of the waste container by adding a layer of concrete of suitable thickness. The concrete layer should be suitably reinforced in order to minimise cracking during curing, transport and filling. The good practice in concrete procurement as discussed in Sections 4.3 and 6.3 of this guide should be consulted. While it is possible to incorporate such a layer of concrete purely for shielding, it would be beneficial also to utilise it to improve the impact performance and fire performance of the waste container.

It should be noted that a level of shielding is also provided by the encapsulation medium, any internal furniture and the waste itself, and this may be taken into account when designing the package, although positional variance and package evolution (for example, movement of unencapsulated wastes due to vibration) must be taken into consideration.

The thickness and density of the shielding provided by a shielded waste container should be selected to ensure that the overall dose consequences during waste packaging and subsequent storage, transport and disposal operations are As Low As Reasonably Practicable (ALARP). However, it will also be necessary to demonstrate that the solution for packaging and disposing of the waste is the Best Available Technique (BAT). Therefore, the use of thicker shielding is not always the optimum approach as this can have consequences for the usable volume of the waste container and result in a greater number of waste packages, transport operations and so on.

The potential use of high density concrete for waste container walls and high density grouts for waste encapsulation can help to reduce external dose. However, the use of lead to provide shielding should be avoided, in accordance with RWM's current arrangements for ensuring compliance with the Groundwater Daughter Directive 2016/118/EC (lead falls into under definition of a non-hazardous pollutant in the Environmental Permitting (England and Wales) Regulations 2010).

5.10 Heat output

The WPSs set limits on the heat generation from waste packages at the time of transport and at the time of disposal vault backfilling.

During normal conditions, when the thermal condition is at a “steady state”, the temperature distributions within and on the surface of the waste package are determined by a combination of:

- Heat output of the wasteform
- Thermal conductivity of the wasteform and the waste container, including spatial variations in material properties and contact resistances between components
- Effective heat transfer resistances due to convective and radiative heat transfer processes in air voids
- Surface finish of the waste package
- Thermal conditions in the surrounding environment, primarily including air temperature and local surface temperatures.

In a fire accident scenario, the environmental thermal conditions will dominate the internal heat generation by the wasteform, leading to a reversal of the direction of heat flow. Given the transient nature of the scenario, the thermal diffusivity governs the rate at which heat may penetrate into the waste container and, to a large extent, the development of internal temperature distribution during and after the fire.

A waste container that has a generally low thermal diffusivity will take longer to heat up, leading to lower final temperatures in the core of the container. Note that local variations in thermal diffusivity and the presence of “thermal bridges” – high diffusivity pathways through the container – may still lead to some local hot spots which significantly exceed the temperature of other nearby components.

The temperature distribution in a wasteform could affect its evolution and integrity, and the temperature distribution in a waste container would cause the waste container to deflect and could also affect its long-term integrity. Although the temperature of the waste container for LHW is likely to be low, deflections likely to be small and effect on long-term integrity trivial, it would depend on the geometry and the material of the waste container. Hence, the temperature distribution in the waste package and the effect of the temperatures on the wasteform and waste container should be understood.

5.11 Surface contamination

Decontamination is the procedure by which radioactive contamination is removed from an item. The process moves undesirable radioactivity from a surface to a carrier (swab, liquid, etc.) from which it can ultimately be disposed of safely and economically. Decontamination is desirable as it reduces the subsequent radiation exposure to workers. Furthermore, it is necessary for compliance with RWM requirements and, where applicable, regulatory limits, such as those for transport. It is well established that the smoother, harder and more chemically resistant a surface is, the easier it is to decontaminate.

It is good practice to design waste containers for ease of decontamination. Design features of the waste container should not create contamination traps. Materials of construction of the waste container and surface finish of the waste container should be chosen for ease of decontamination.

The requirement regarding surface contamination for each waste package type is defined in their respective WPS. For waste packages that are transport packages, TCSC codes of practice TCSC 1080 [64] and TCSC 1088 [65] should be consulted in addition to the guidance below.

5.11.1 Stainless steel containers

The surface finish applied to the surface of stainless steel waste containers should be consistent with the twin aims of corrosion resistance and ease of decontamination. Standard surface finishes provided by steel suppliers may be adequate, but a post-fabrication treatment would usually be beneficial. This would ensure that heat-tint, superficial damage and minor contaminants are removed, and would provide a uniform baseline condition for the packages.

The potential for packages to require decontamination should be considered when determining the required surface finish. Historically, many nuclear plant designs have been based on placing the empty container wholly within the active environment, accepting that the container could be contaminated externally, and providing a decontamination station prior to its export to storage. Accepted good practice is now to provide a sealed waste delivery system within a shielded environment, thus preventing external radioactive contamination. In this case, there is less need for an easily decontaminated surface.

Mechanical polishing can produce a high quality visual finish but this may not be fully compatible with the aims noted above. This is because of the lateral polishing action, which results in flattening of high spots on the original surface, potentially leading to contamination traps, as well as microscopic crevices that could promote corrosion. Alternative mechanical methods, such as wet bead blasting, provide an orthogonal rather than lateral mechanical action, and will tend to remove high spots completely, and thus be more consistent with material longevity.

Chemical methods of cleaning, such as pickling and passivation, offer a very effective and useful alternative to mechanical abrasion. This approach will remove surface roughness by preferentially dissolving material from high surface area locations on the surface, resulting in a smoothly undulating surface. It is important that chemically treated surfaces are adequately rinsed to ensure that ongoing corrosion is halted and the passive surface layer of the underlying metal is restored.

In the light of this discussion, a numerical target for surface roughness is not currently considered to be appropriate. Instead, waste producers should take account of the specific circumstances of material supply, handling and storage, and of the conditions of fabrication of the waste containers, and devise a surface finish strategy consistent with the required longevity of the waste package.

5.11.2 Concrete containers

The outer surface of a reinforced concrete container should be specified to achieve a smooth finish, free from projections or unevenness of the surface. However it is also necessary to limit the degree of surface air voids and the degree of water absorption at the surface.

The selection of the formwork system should be appropriate in order to avoid localised surface defects that may compromise the long-term durability and/or compromise the decontamination treatment of the container.

To facilitate the decontamination treatment of the surface, the specification of concrete finish should be “plain finish” in accordance with Table F.4 of BS EN 13670: 2009 Execution of Concrete Structures [66], taking into account the following additional requirements:

- An even matt finish of uniform texture
- Limit the extent of blow holes, surface air voids and other surface defects
- Any formwork lining should be so joined and fixed to its backing that it imparts no irregularities to the concrete surface; it should be of a single type and obtained from only one source throughout any one structure
- Imperfections in the finish should be made good
- The achieved flatness and finish should be documented in the inspection report in accordance with the principles established in CEN/TR 15739 Precast Concrete Products – Concrete Finishes – Identification [67].

5.11.3 DCI containers

A surface coating is typically applied to the surfaces of DCI containers to improve corrosion performance and for ease of decontamination. The use of multi-coat organic systems consisting of a zinc-rich epoxy primer with primarily an epoxy resin base layer is recommended as good practice for the surface coating of packages [68]. Whilst this is not a requirement, it has been recommended [67] that the choice of surface coating considers the following issues:

- The substrate surface preparation, application of the coating and curing are critical to achieving optimum performance and durability.

- The dry temperature tolerance of the coatings should be significantly greater than that required during the container lifecycle (including during waste drying and backfilling).
- Epoxy resin coatings have a high resistance to relative humidity and are expected to maintain their durability during interim storage and GDF operational periods, assuming the relative humidity of the facilities is controlled to <80%.
- The coating systems specified should have sufficient resistance to aggressive species such as chloride and sulfate and are should not degrade significantly under the concentrations expected prior to the post-closure period for the GDF.
- The radiation level on the external surfaces of the containers is not expected to be high enough to have a significant effect on the durability of any coating, but this should nevertheless be confirmed.
- The durability of epoxy-based systems is considered to be high in comparison to other organic coating systems.
- Surface coatings should be easily decontaminable.

5.12 Gas generation

Many wastes have the potential to generate gases by a number of different mechanisms, and at different times, during their long-term management.

Pressurisation could cause deflection or even damage to sealed waste containers. Waste containers should therefore be vented if gas production by the wasteform, over the period during which the waste package may need to be handled (that is, on-site, during transport and during the GDF operational period), is considered capable of causing pressurisation of the waste container. In this context, pressurisation is of particular concern where it could exceed 0.5 bar (gauge), as the Pressure Systems Safety Regulations [69] would then apply.

Two generic approaches can be adopted for venting the waste container to ameliorate the effects of gas generation by the wasteform contents:

- The incorporation of an engineered vent into the waste container
- The use of a waste container that is manufactured from a gas permeable material, for example, concrete, as long as the gas pathway from the wasteform to the waste container is not blocked by an impermeable material, for example, a steel liner.

The presence of an engineered 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. This leads to the requirement for the vent to be filtered, which could, for example, be achieved by the use of a proprietary high efficiency particulate in air (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 also potentially conflicts with a need 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 (for example, through an ineffective body/lid seal), that could result in the filtering system being bypassed particularly during the earlier, more reactive phases of wasteform evolution. Unless a waste container constitutes the containment boundary of a Type B package during transport, it should be noted that there is no specific requirement that a waste container needs to incorporate a seal at the lid-body interface, as long as it can be demonstrated that the lid-body interface does not present an alternative gas pathway as discussed above. A number of existing waste package designs do not employ a seal at the lid-body interface.

The following are guidelines on the design of a filtered venting system:

- 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.
- When considering designs of the venting systems, the designer should take into account the long-term integrity requirements for the waste package. 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 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 (for example, 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.

The ONR guide to the use of elastomeric seals in transport packages [70] should be consulted for good practice in the design of seals.

Gas permeability of concrete depends on the composition of the concrete (especially its water-cement (w/c) ratio and cement type as these determine the pore structure of the concrete) and also on the moisture state of the concrete (that is, the proportion of pores that are filled with water) which is in turn related to its age. Concrete Society Technical Report 31 [71] should be consulted for good practice in measuring concrete permeability and for typical values for information.

It should be noted that some wastes could generate hydrogen during their long term management. This issue should be considered during the design of the wasteform, but may also need to be considered during the design of the waste container.

5.13 Criticality safety

Guidance on the criticality aspects of waste package designs is discussed in the guidance on the production of encapsulated and unencapsulated wasteforms [10, 11], so not discussed in detail here. Further guidance is also available in WPS/625 [72], WPS/911 [73] and WPS/916 [74] and these should be consulted.

In terms of the effect of the design of waste containers on criticality safety, it is sufficient to note here that:

- The waste container should not include any feature that could adversely affect the criticality safety of the waste package
- The waste container designed-in furniture should be utilised to provide confinement and separation of fissile materials
- Neutron moderating materials should be avoided in waste container designs.

5.14 Impact performance

5.14.1 Introduction

The impact accident scenarios and the performance criteria for waste packages in the impact accident scenarios are outlined by RWM in [75].

Under all credible impact 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.

This section presents good practice to improve performance in impact accidents, in drops onto flat targets and in drops onto aggressive targets, followed by good practice regarding means to demonstrate impact performance.

5.14.2 Good practice to improve impact performance in drops onto a flat target

It is important to understand the behaviour of waste packages during an impact before prescribing any design solution to improve their performance. Therefore, the following sub-section provides an overview of the behaviour and then discusses good practice in improving the performance of waste packages during a drop onto a flat target.

Understanding the impact behaviour

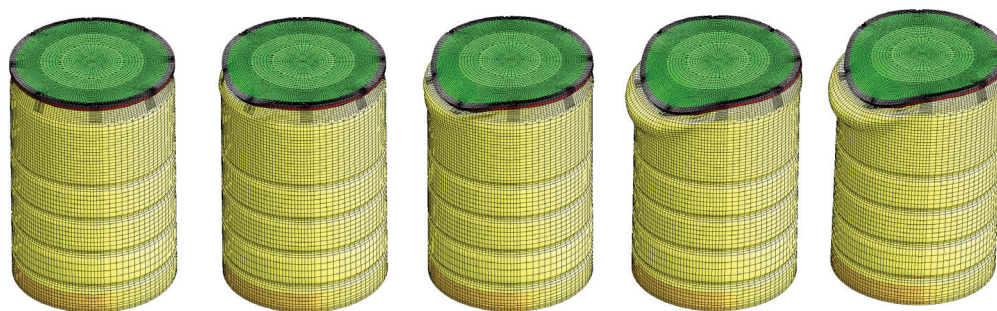
When a waste package impacts a target after a drop, it will deform to absorb the kinetic energy which it possesses at the start of the impact. The waste package will decelerate, and may rotate and/or rebound. How it will deform, decelerate, rotate and rebound, depends on:

- The design of the waste package
- Its impact orientation
- The drop height
- The nature of the target.

Unshielded packages and shielded packages with a stainless steel container

The impact behaviour of a typical unshielded waste package and of a shielded waste package utilising a stainless steel container, are best illustrated by considering an impact accident scenario involving a single skin 500 litre drum impacting a flat unyielding target in a centre of gravity over lid edge orientation. Snapshots of it as simulated by finite element method is shown in Figure 6.

Figure 6: Deformation of a typical 500 litre drum in a centre of gravity over lid edge drop onto a flat unyielding target, as simulated by finite element method



The behaviour can be described as follows.

- During impact, the waste package is compressed against the target by its own momentum. The steel lid flange, which makes initial contact with the target, dents locally.
- As the impact progresses, the lid bends, the body flange bends, the neck buckles and folds, and the impacted edge is progressively “knocked back” into the package.
- Simultaneously as the steel shell deforms, the grout encapsulated wasteform in the vicinity of the impact crushes. As it crushes, it sends cracks into the rest of the wasteform.
- The wasteform near the top of the drum spills into the ullage.
- As the crushed wasteform is contained by the drum, there is no escape path, so that, as impact progresses, the movement and increasing knockback grinds crushed wasteform to even finer particulates.
- As the contact area between the package and the target increases, the rate of knockback slows down and the rate of particulate generation reduces eventually to zero.

- The continuous compression of the package onto the target by its own momentum until the package rebounds grinds the particulates and compacts them.
- As the package is knocked back, its internal volume reduces. If there is any breach in the containment, air would be pushed out through the breaches, and may carry with it some of the loose particulate. If the breach is large enough, larger pieces of crushed wasteform (or inactive cap or grout annulus) may fall through.

Reinforced concrete packages

When a waste package based on a reinforced concrete container impacts a flat unyielding target in a centre of gravity over an edge or corner orientation, the concrete outside of the reinforcement cage in the vicinity of impact can be expected to crack and spall (that is, crack and fall off) as soon as the package impacts the target. As the impact progresses, a progressively larger volume of the concrete would spall. How extensive the spalling would be, how the container would hold together, or how much of the wasteform would crush, will depend very much on the robustness of the waste container and the support that would be provided by the wasteform.

If the reinforcement system is suitably designed and there is adequate ductility in the wall structure, even if the exposed concrete outside of the reinforcement has spalled and the concrete within the reinforcement cage is cracked, it could still hold together. A steel cladding that has an adequate thickness and is adequately attached to the reinforcement cage, even if it is present only locally covering the corners and edges which are the most vulnerable areas of a container in an impact, could improve the behaviour by absorbing energy and by providing containment to the concrete hence improving its ductility.

As with all waste packages, the weakest area in a reinforced concrete package is the interface between the lid and the body. This interface would typically consist of a “cold joint”⁸ as the lid would have been cast after the body has been set, and a discontinuity or a weakness in the reinforcement system.

One of the key mechanisms that causes particulate release in typical unshielded packages, and shielded packages using a steel container, is the airflow from the package caused by reduction in the internal volume associated with the knockback deformation. Such airflow drives particulates out through breaches in the containment. As long as there is no airflow, there will be no mechanism to drive loose particulates out. Therefore, in the case of a reinforced concrete container, if it is sufficiently robust such that deformation is largely confined to the waste container structure, then even if the concrete cracks, release of particulates by flow of air from the inside to the outside of the package could be minimal. One of the advantages of a reinforced concrete container in impact is that the wasteform is inherently distanced from the impact by virtue of the thickness of the container, and the container acts as an energy absorber reducing the energy that is passed onto the wasteform.

⁸ “Cold joint” is a terminology used for any joint in concrete where the matrix is broken by a crust layer. It is essentially any joint that follows an interruption in the wet concrete placement process. It does not necessarily mean the concrete will be thermally cold. A reasonably stiff crust could form within between 1 and 6 hours, depending on the concrete mix.

Robust shielded packages

In an impact of a robust shielded package, the package will deform where it makes contact with the target, although the extent of such deformation is expected to be considerably smaller than in other types of waste packages. Knockback will be larger and deceleration will be lower in impact orientations in which the area of contact with the target is smaller. Knockback will be smaller and deceleration will be higher in impact orientations in which the area of contact with the target is larger. Typically, knockbacks are highest if the corner of the package impacts the target, and knockbacks smallest if the package impacts the target with its base, lid or one of its sides. Decelerations are lowest for impacts on corners and highest for impacts involving the base, lid or one its sides.

Reaction force on the waste container from the target causes the waste container to deform plastically, locally in the vicinity where it contacts the target. If the material does not have adequate ductility, it could fracture.

In addition to the local deformations at the vicinity of contact with the target, the loading also causes global/overall deflections of the waste container structure.

Deceleration has much greater significance for packages where the content is unencapsulated than for packages with encapsulated content. The encapsulated wasteform supports the waste container structure to minimise deflections in the waste container caused by the inertial loading. In a base down drop of a typical robust shielded box package, the loading would cause the lid to flex in a “dishing” type deflection, to load the bolts in a prying type loading as well as causing the walls to bulge. This would be exacerbated by rebound of the body, as the lid would still be deflecting downwards.

Methods that can be employed to improve impact performance in drops onto flat target

Through careful design, a waste package can be designed to perform well in impact accident conditions, and have minimal release even when it suffers large deformation. The key methods for improving impact performance are discussed in turn for packages manufactured from a stainless steel container, a reinforced concrete container and a DCI container below.

Unshielded packages and shielded packages with a stainless steel container

Both the waste container and the wasteform contribute to the impact performance of a waste package. While it is possible to design the wasteform to be more impact resilient (for example, by encapsulating it in a less friable encapsulant), this may prove to be unachievable for the reason that there are already many other factors to be taken into account in designing a wasteform; to design it for impact performance is unlikely to be a priority. Instead, the waste container should be designed to achieve the required impact performance for the package.

The key strategies to improve impact performance are as follows:

- Minimising the extent to which the wasteform crushes, thereby minimising the particulates available for release.
A layer of plain grout or concrete between the waste container and the wasteform (for example, annulus, capping, concrete shielding) is extremely useful for improving impact performance. This distances the wasteform (which contains activity) from the surface of the waste container hence (a) reducing the volume of the wasteform that would be crushed and reducing the amount of particulates that could be generated from the wasteform; and (b) increasing the distance the wasteform particles must travel from the area where they are generated to the breach in the containment, hence increasing the amount of active particulate retained within the crack before it can be released.
- Improving the integrity of the lid to body interface.
The lid-body interface is typically the most vulnerable area in the containment of most waste packages and typically the lid is connected to the body by bolts. Strategies to improve the chance of survival of the lid-body bolts in impacts include:
 - Placing the bolt heads in recesses in the lid flange to avoid direct contact with the target as the lid flattens against the target.
 - Employing spigots at the lid-body interface to resist shear displacement between the lid flange and body flange. For drum type waste containers, the spigot should be on the inner perimeter of the body flange or outer perimeter of lid flange to resist shearing as the lid is pushed across the body during contact with the target. For box type packages, the required location of the spigot depends on the location around the perimeter of the lid, as the direction of shear of the lid flange with respect to the body flange varies with location.
 - Selecting a bolt material that has a high energy absorption capacity (that is, a large area under the force-deflection curve) rather than merely “high strength”.
 - Using larger bolts such that the force that loads the bolts is carried by a larger bolt cross-section area.
 - Reducing the thickness of the lid and lid flange so that the loading on the bolts due to lid prying is reduced.
 - Reducing the size of the lid so that the bolted interface is smaller and further from the impact site, although this is contrary to common requirement to enlarge the lid to facilitate waste loading.

- Improving the integrity of the waste container.
Although the lid-body connection is often the weakest area of the containment, other areas, if designed inadequately, could also fail in impact. The means to improving the integrity of the waste container in impact include:
 - Moving welds away from edges and corners. The reason is that if an edge or a corner is the leading edge/corner in an impact, it would be “flattened” as impact progresses and the weld, if located at the edge/corner, would act as a “hinge” between the adjacent walls which flatten onto the target and hence be subjected to very significant strains. Considering that the weld and the HAZ are often somewhat less ductile than the parent metal, and it is difficult to define their mechanical properties precisely, it would be prudent to locate the weld away from an area that is subjected to such large strains. One way to achieve this is by using pressed parts.
 - Using full penetration butt welds instead of partial penetration butt welds or single/double sided fillet welds. Fillet and partial penetration welds have an inherent “notch” at their roots which may limit their ductility during impact. In addition, the behaviour of full penetration butt welds is more amenable to analysis and is more predictable in large deformation situations, as found in impact scenarios. Fillet and partial penetration welds are less amenable to analysis and therefore there is less certainty with how they will behave in reality.
 - Avoiding abrupt changes in thickness, which often lead to stress concentrations and failure, by tapering changes in thickness.
- Making use of the furniture (for example, anti-flotation plate and liners) to improve impact performance.
In many package designs, furniture of various types is required for operating, waste filling and conditioning purposes and such items can be utilised to improve impact performance. For example, by virtue of its connection to the rim of the opening, an anti-flotation plate in waste packages with a large opening could be designed to stop the fractured wastefrom from impacting the underside of the lid and to restrain the fractured wastefrom from release, acting like a secondary containment. By incorporating stiffeners in vertical and horizontal directions, a liner could also be stiffened to minimise its own deflection in the impact and maximise the energy absorbed in the annulus thereby reducing the energy absorbed in the wastefrom.

Reinforced concrete packages

For concrete packages, the strategy is to improve the ductility and robustness of the waste container and improve the integrity of the lid-body interface. The following should be considered:

- Employing steel collars of an adequate thickness at the edges of the waste container and connect the collars to the reinforcement case. The purpose is to protect the most vulnerable areas of the waste container, so that in an impact the concrete will not easily spall.

- Having adequate reinforcement in the concrete, with bars in orthogonal directions and at inner and outer surfaces of the section. The bars should be welded to achieve a more resilient and robust reinforcement cage. Inner and outer layers should be connected by tie-bars. This is to achieve a ductile reinforcement cage which will maintain integrity even if the surface concrete has spalled off.
- Ensuring continuity of reinforcement and employing shear keys between the lid and the body at the lid-body interface. The reinforcement bars spanning the lid-body interface should be designed to cope with the strains due to the relative displacements between the lid and body across the interface. Mechanical connections in addition to or as an alternative to the reinforcement bars should be considered to maintain the integrity of the interface. A steel collar as discussed above, which has adequate thickness and stiffness, could also be utilised to help maintain integrity of the interface.
- Keying the wasteform to the body of the waste container such that in a lid corner or lid edge impact, the wasteform does not present a “battering ram” type of loading onto the lid.

Robust shielded packages

The strategy to improve impact performance of robust shielded packages is different from those for other package types. For robust shielded packages, the waste container’s enhanced integrity compensates for the reduced contribution from the wasteform. However, the degree of containment required depends on the nature of the waste. If it is known that particulates would or might be present at significant activity levels, the safest strategy is to aim for no gross loss of containment. Transient deflections and opening at the seal faces during the impact are unavoidable. Permanent deformations are acceptable as long as there is no significant loss of containment. With this strategy, the containment should be designed to well-established strain-based performance criteria. Such criteria require the strain in the structure to be evaluated against failure strain value for the triaxiality at the locations being evaluated. The criteria should also take into account the effect of temperature and strain rate. Since the behaviour of DCI is strongly dependent on the composition of the material and the manufacturing process, the criteria could be expected to vary with different DCI formulations and foundries. Both ductile and brittle deformation behaviour should be taken into account in the design.

To improve impact performance, the following design details have been found by experience to be important:

- Making corner radii as large as possible to minimise stress concentrations
- Minimising lateral clearance between the lid and the body (for example, between the edge of the lid and an up-stand of the body, to facilitate insertion of the lid into the body) to minimise the extent of deflection possible in the body
- Designing lid bolt hole geometries such that, even with movements of the lid with respect to the body, the bolts are not stressed beyond their limits
- Stiffening the structure to minimise global deflections
- Utilising local features (for example, protrusions around the handling points) to limit the decelerations in drops onto the lid, the base and the sides

5.14.3 Good practice to improve impact performance in drops onto an aggressive target

Understanding the impact behaviour in a drop onto an aggressive target

Flat targets are not the only target type that a dropped waste package in the GDF may encounter. Unless designed out of the GDF as design work progresses, a dropped waste package may land on GDF features, installed equipment or other waste packages co-located in the same vault. Certain features of these items, for example the top edge or top corner of other waste packages, could be aggressive for the dropped waste package. These features are referred to as aggressive targets. RWM has defined drops onto an aggressive target as one of the impact accident scenarios against which the performance of a waste package has to be demonstrated [74].

RWM has carried out studies to identify the bounding aggressive targets for unshielded waste packages and shielded waste packages by considering all potential handling accident scenarios in the GDF [76,77] and concluded that bounding aggressive targets are typically the top edge or top corner of other waste packages that are co-located in the same vault.

In drops onto flat targets, given a specific drop height, the drop orientation is the only parameter that would affect the behaviour of the package. In impacts onto an aggressive target, drop orientation as well as the point of initial contact with the aggressive target would affect the behaviour of the package during the impact. However, the point of initial contact on the dropped package and the contacting feature of the target package that constitute the worst combination would depend on the respective designs of the dropped package and the target package.

In the drop onto aggressive target scenario, the focus is typically the performance of the dropped package. The damage of the package that is the target is likely to be bounded by the damage in its own drop scenarios, and because it is stationary and has no momentum of its own, even if its containment is breached by the dropped package, its contents are likely to disperse less than in its own drop scenarios. However, it is necessary to confirm that the performance of the target package will indeed be bounded by its own drop scenarios, and in any case, its performance should be demonstrated in addition to that of the dropped package.

Unshielded packages and shielded packages with a stainless steel container

For unshielded packages and shielded packages with a stainless steel container, the lid is typically the most vulnerable area in an impact onto an aggressive target.

Although the lid-body interface is often the most vulnerable area in an impact onto a flat target, in an impact onto an aggressive target, flat areas (for example, the middle area of a lid) are typically more vulnerable. The reason is that the lid-body interface is typically located at an edge or close to the edge. If the package is oriented so that the area is directly impacting the aggressive target, the angle would either be so steep that the package would skid off the target, or the angle is shallow such that the package would rotate off the target.

The sides and the base of waste packages are normally not vulnerable as the sides and the base of the container would normally be supported by the encapsulated wasteform.

If the package is oriented with the lid facing downward, and making contact with the aggressive target, the lid could puncture and continue to tear as the package descends. The package would then decelerate rapidly when its flanges bear onto the top edges of the aggressive target, and rotate off the target. As the lid punctures and deforms, the perimeter of the lid would be pulled “inwards” towards the point of impact and this would impose shear loading on the lid bolts. Substantially thickening the lid, utilising spigots at the lid-body interface to counter the shear loading, and employing a thick inner lid, are some possibilities to improve the performance of these packages in impacts onto an aggressive target.

Reinforced concrete packages

For reinforced concrete packages, the lid-body interface is often the weakest area. However, this area is unlikely to be seriously threatened by an impact onto an aggressive target, as it is often located near the top edge of a package, and hence the package would rotate or skid off the aggressive target if an aggressive target is to make contact with the package at this area. Besides the lid-body interface, there is typically no other area which is substantially weaker than the rest of the package.

For packages where there is a steel cladding partially covering the outside of the package, the exposed concrete area would be weaker in impact than the clad areas. Typically, if the package is to impact the aggressive target with a plain unclad area, the outer layer of concrete would crack and spall, the reinforcement would bend and the concrete in between the reinforcement layers would crack and crush, with cracks extending into the package. Depending on the strength of the reinforced concrete section, the wasteform adjacent to the impact area can also crush.

Generally the performance of concrete packages in impacts onto an aggressive target would not be much worse than an impact onto a flat target. It should also be noted that the impacting package is also similar in strength to the aggressive target, so the aggressive target is likely also to absorb some of the energy of the impact.

Robust shielded packages

For robust shield packages, an impact onto an aggressive target is a very onerous impact scenario. With a wasteform that is typically non-encapsulated, the contents will not provide any support to the container structure. The worst impact positions to impact the aggressive target would typically be its lid, base or sides (rather than edges or corners).

Besides causing local indentation, the impact will bend the wall of the structure to generate tensile stresses on the inner side of the wall. If the wall is not thick enough, and if the material does not have adequate ductility, the wall can crack starting from the inside where it is experiencing tension.

Methods that can be employed to improve impact performance in drops onto aggressive target

Unshielded packages and shielded packages with a stainless steel container

In impacts onto an aggressive target, the lid area is the most vulnerable area in unshielded packages and shielded packages with steel containers. The lid is likely to be punctured, although the lid-body flanges are often adequate to slow the progress of the aggressive target into the waste package. The strategy to prevent lid puncture is to increase the thickness of the lid, or alternatively to include a thick inner lid or to improve the resilience of the anti-flotation plate to minimise ingress of the aggressive target.

Reinforced concrete packages

For concrete packages, it is thought that its performance should be similar to its impact onto a flat target and no additional measures are required.

Robust shielded packages

For robust shielded packages, the strategy would simply be to take this impact scenario into account when designing the package, so that the design is robust in impacts onto a flat target and impacts onto aggressive target. Dimensions and geometry should be adjusted taking into account all the different requirements from the different impact orientations until a satisfactory performance is obtained.

5.14.4 Good practice to demonstrate impact performance

Guidance regarding the choice between analysis and testing

Impact performance of waste packages could be demonstrated by analyses, drop tests, or a combination of the two. Drop tests are seldom adequate on their own as the information that can be obtained is limited. Analyses, for example, computer simulation with the finite element method, may not be adequate on their own, as an analysis is essentially a mathematical model of reality, and analyses need to be benchmarked against drop tests to show that the simulations are realistic. In order to decide, and to justify, whether drop tests need to be carried out in addition to analyses the following factors should be considered:

- The competency of the team that is carrying out the analyses and what is their track record in the analyses of similar packages.
- The complexity of the design of the waste package and its behaviour in the impact scenarios; what is the level of uncertainty in the behaviour of the waste package, including complexity due to deformation/deflection behaviour and uncertainty in material behaviours?
- The safety margins in the package, for example, for low hazard contents, larger uncertainties may be tolerable.

- The provenance of the waste package design that is analysed, that is, how similar is it to previous waste packages for which impact performance has been demonstrated?
- The provenance of the analysis model, that is, is the analysis model based on an existing model that has already been benchmarked against drop tests?
- Whether component level benchmarking has been carried out and the benchmarked component models used in the overall model, for example, modelling of the bolts and modelling of the waste container material?
- Whether the modelling, analysis and checking comply with established good practice as defined in TCSC 1087 [77]?
- Whether sensitivity analyses have been carried out to assess the sensitivity of the results with modelling parameters and quantities that are unknown?
- What is the uncertainty in the behaviour predicted by the analyses?

There is no rigid rule that defines whether analyses are adequate on their own to demonstrate impact performance, how many drop tests need to be carried out to benchmark the analyses, or how analyses and drop tests should be combined to demonstrate the impact performance. Other factors, for instance cost, industrial safety or regulatory expectations, may affect the balance between analysis and physical testing.

Each waste package design will need to be considered on its own merit, considering the above points, and a good argument put forward to justify the strategy.

Good practice in finite element analysis and drop tests

Good practice guidance on the use of finite element analysis for impact events and for drop testing has been produced by the Transport Container Standardisation Committee, TCSC 1087 [78] and TCSC 1086 [79] respectively. These documents should be consulted.

Component level benchmarking

In addition to benchmarking of finite element analysis with drop tests as mentioned above, component level benchmarking should also be considered. The behaviour of specific components of waste packages, especially the bolts, the wasteform, and the material of the waste containers, has a significant influence on the overall behaviour of the waste package in impact events. The model of these should be benchmarked against tests to improve the robustness of the overall model.

An extensive programme of tests on bolts, grouts and concrete, in loading scenarios that simulate the loading during waste package impact scenarios and relevant for deriving material properties for input to material models, have been carried out by RWM [80,81,82]. These tests should be considered for the component level benchmarking of the finite element model of these components.

Combined test/analysis methodology

While the finite element technique is useful for the simulation of structural behaviour, such as deformations, stresses, strains and material failure, it cannot simulate the particulate breakup of wasteforms or predict release fractions. Although the latter can be measured in drop tests, there is uncertainty with the accuracy of such measurements especially with the relatively small masses of material released. RWM has therefore developed an approach that combines finite element simulation with the results of wasteform breakup tests to determine waste package impact performance in terms of particulate generation for waste packages with encapsulated wasteforms. This methodology is defined in [83] and may be used to evaluate the impact performance of waste packages. However, it should be recognised that at present, this method provides an extremely conservative estimate of release, although development is being carried out to reduce this conservatism.

5.15 Thermal performance

There are two aspects to the thermal performance of a waste package: its performance under normal conditions and its performance in the fire accident scenario. Under both normal conditions and fire accident scenarios, the performance of a waste package is dependent on the thermal behaviour of both the wasteform and the waste container.

5.15.1 Thermal performance under normal conditions

The WPSs set limits on the heat generation from waste packages at the time of transport and at the time of disposal vault backfilling.

As discussed in Section 5.10, the rate of heat generation by the wasteform, temperature distribution of the wasteform, thermal conductivity of the wasteform, and thermal conductivity of the components of the waste container would affect the temperature distribution in the waste package.

All solid materials expand in response to heat. And when the temperature distribution in a structure is not uniform, or the different components in the structure have different coefficient of thermal expansion, the structure would deflect in response to the temperature distribution.

For LHGW, the temperature of the waste container is likely to be close to ambient and any deflections due to different thermal expansion are expected to be small. However, this does depend on the heat output from the wasteform, the thermal conductivity of the waste container, and the geometry of the waste container. The waste container should be designed such that deflections and strains in the structure due to temperature distribution do not compromise its structural performance or its long-term integrity. It also should not suffer any permanent deformation or abnormality due to the temperature distribution.

5.15.2 Thermal performance under fire accident scenarios

The fire scenarios and the performance criteria for waste packages in the fire scenarios are outlined by RWM in [74].

Under all credible thermal 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.

Heat transfer through the waste package is a slow but predictable process and the centre of the waste package may not experience its maximum temperature until several hours after the fire has been extinguished. Possible sources of uncertainty lie in the precise values of the thermal conductivity, heat capacity and density of the material components of the waste package and the impact of microscopic air gaps between adjacent components (that is, contact resistances).

The principal concern about waste package performance in the event of a fire is that heating of the wasteform could cause radionuclides to be released.

The waste container performs an important function in achieving the required waste package performance in fire accident conditions by limiting the temperatures experienced by the wasteform and by providing a containment to minimise the release. Good practice in the design of waste containers for the fire accident scenarios is discussed below in turn for waste packages manufactured from a stainless steel container, a reinforced concrete container and a DCI container.

Although the fire scenarios are defined as fully engulfing fires, it should be noted that waste packages are stacked in the GDF. The waste package designer should quantify the package response to fire when the package is within a stack, to ensure that there is no loss of stack stability during or after the fire scenario.

Unshielded packages and shielded packages with a stainless steel container

Under accident conditions, the performance criteria are that release should be low and predictable. For both an unshielded package and a shielded package, which have a steel container on the outside, the primary barrier to the external heat source is the stainless steel container. This protects the wasteform from direct contact with the flames and an oxygen source, and the amount of oxygen entering through a filtered vent of the stainless steel container would be extremely limited. It has been demonstrated that the integrity of a stainless steel waste container can remain good even following a severe fully-engulfing pool fire.

The steel container is typically only a few millimetres thick, except for thicker components like flanges, aperture plates and stacking plates. Stainless steel has a high thermal diffusivity and would heat up rapidly when engulfed in a fire. It is therefore the thermal properties of the contents of the waste container (including the shielding of a shielded package) that have a key influence on the temperature distribution in the wasteform. Most waste packages rely on grout to encapsulate the waste, and some have a grout annulus or concrete shielding. These are good insulators and may provide good thermal shielding to the waste. However, the location of the activity relative to the surface will affect how much thermal shielding they can provide.

Some design considerations for stainless steel waste containers for the fire accident scenarios are as follows:

- The waste container should be designed to eliminate or minimise the effect of internal furniture items providing short-cut heat pathways (also known as thermal bridges) to central regions of the wasteform.
- To connect internal furniture to the waste container wall, non-metallic components, for example, concrete spacers, should be considered instead of steel spacers. If the use of metallic connections cannot be avoided, their thickness should be minimised to ensure that the potential heat load towards the wasteform can be effectively dispersed into the surrounding grout and wasteform.
- If added thermal protection is required, then thermal shielding could be incorporated into the design, for example a grout annulus. It should be noted that most thermal shielding is not unidirectional, in that it will provide protection for the wasteform from an external fire, but could also provide a barrier to the release of internal heat. The thermal properties of the waste package should be assessed to ensure that normal internal conditions, including the heat of hydration (curing) of cementitious wasteforms, do not result in temperatures within the wasteform that can lead to degradation of the package.
- Gas generation from the waste package will increase during a fire, particularly from steam generation arising from the drying of grout encapsulant or other water-containing materials. The flame temperature of the fire is expected to degrade items such as nitrile rubber seals and fine stainless steel mesh used in some vent filters, which would increase the area for venting under such accident conditions. Studies have shown that retention of radionuclides by the wasteform in these circumstances is very good. However, it is generally pessimistically assumed that the waste container does not provide any retention for the volatilised radionuclides to the external environment. Consideration should be given to ensuring that such pathways are available to avoid pressurisation, as well as confirming that for a pressurised container failure would be benign and predictable.

Reinforced concrete packages

The heating of reinforced concrete in severe fires creates the individual and combined effects of the following response parameters:

- Loss of strength and stiffness in the concrete, reinforcing steel and any other materials embedded in the package, such as lifting brackets and security furniture
- Direct thermal expansion of the materials
- Thermal bowing of concrete components due to the thermal gradient between the exposed face and unexposed face of the box
- Cracking of the concrete due to increased forces caused by restrained thermal expansion and the rotations created during thermal bowing
- Spalling at the concrete surface and through its depth.

The designer must quantify the development of heating through the whole of the package over the whole period of the design fire exposure. The designer must then quantify the response parameters listed above individually and together for the entire design fire duration to demonstrate that the required performance criteria will be met when the package is exposed to the defined design basis fire. This is particularly important where:

- There are cold joints in the structure, for example when the package lid is cast after the package has been filled with the grout/waste mix
- There are steel lifting brackets or other similar embedded metallic items in the structure.

It should be noted that spalling cannot currently be quantified by calculation. Guidance to assessing spalling is provided in the report *Fire Resistance of Concrete Enclosures* [84]. The following parameters are known to affect the likelihood of spalling:

- Moisture content in the concrete
 - Mechanical restraint
- Applied load
 - Porosity/permeability
 - Concrete strength
 - Aggregate choice
 - Heating condition
 - Presence of reinforcing fibres.

The designer must demonstrate that the package design will not be affected by spalling, such that the performance criteria would not be met.

Guidance on how to mitigate spalling in concrete is provided in Sections 4.5 and 6.2 of Eurocode 2 (BS EN 1992-1-2:2004) [22] and this should be consulted.

Reinforced concrete packages are complicated systems as far as fire performance is concerned. Interactions between the sides and lid of the structure, metallic cladding/ items on the outside, reinforcement bars, the wasteform, and moisture movement through the structure all require consideration.

The preamble of the Eurocode 2 states that “*Unusual forms of construction or design conditions are not specifically covered and additional expert consideration will be required by the designer in such cases.*” Therefore the waste container designer cannot rely solely on calculations but must demonstrate that their design is supported by directly applicable fire test data.

During manufacturing, fabricators sometimes use higher grades of concrete than those specified in order to achieve improved mix performance for fabrication, such as higher early strength or workability. However, the likelihood of spalling increases with increase in concrete strength. The designer should therefore ensure that the fabricator does not use a higher grade of concrete than specified.

Robust shielded packages

A typical DCI container has walls in the region of 50 mm to 300 mm thick to meet impact and shielding performance requirements. Such thick walls will retard the flow of heat into the core of the container during the early stages of the fire scenario due to their high specific heat capacity and density. However, towards the end of the scenario they may provide limited resistance to the flow of heat due to their relatively high thermal conductivity. Heat transfer through the waste container is a slow but predictable process and in a fire accident scenario, the internal surfaces of the waste container may not experience their maximum temperature until several hours after the fire has been extinguished.

The design strategy should be to increase the thermal mass in the containment seal area so as to limit the temperature of the seal, ideally to within its operating regime, during the fire scenario, and so that any deflections of the waste container structure due to thermal gradients do not cause the seal to be compromised.

A further consideration is the nature of the wasteform, particularly its volatility and moisture content and therefore its propensity to produce gas or steam. It may be possible to ensure that wasteform temperatures remain below those of concern (<100°C), but this is unlikely. If it is not possible to keep the temperatures of the wasteform below those of concern, filtered vents should be installed to contain particulate radionuclides to HEPA standards but allow gases to vent and so mitigate concerns over pressure rise and container integrity.

6. Manufacture

6.1 Introduction

All materials used in the production of a waste container should be chosen and sourced such that they perform their required function over the temperature ranges envisaged during on-site storage, transport to GDF and operational period of the GDF.

The waste container should be designed and manufactured such that sufficient inspection by appropriate means can be carried out, to ensure that the required quality is achieved.

A manufacturer should be engaged in the design process to ensure that the design is suited for manufacturing.

Guidance on the manufacture of stainless steel containers, reinforced concrete containers and DCI containers is discussed in the sub-sections below.

6.2 Good practice in the manufacture of stainless steel waste containers

6.2.1 Choice of fabrication technique

The majority of stainless steel waste containers are currently produced by processes involving the fabrication of plate or sheet materials. When selecting fabrication methods, for example, cold forming (pressing, bending, deep drawing, spinning), machining and welding, it is recommended that welding should be minimised as far as possible. The basis of good fabrication is that welds should not be used where they are not required. When welds are used:

- Their size and volume should be kept to a minimum
- Automatic processes are preferable to manual processes, with the former often requiring less preparation and offering more consistency in weld quality.

It is recommended that alternative fabrication methods should be evaluated and that combinations of methods are used where appropriate. The evaluation should take into account the following points:

- Amenability of the specific material under consideration to the different fabrication methods, for example, pressing, welding, machining
- The geometry required
- Mechanical performance requirements
- Corrosion aspects
- Ease of decontamination – design features should not create contamination traps and should facilitate decontamination by proven nuclear industry techniques
- Ease of achieving consistent quality and minimising defects in manufacturing runs
- The number of containers required, for example, pressing may only be justified on large production runs because of the additional cost of press tools
- Cost
- Assembly and fabrication sequence
- Ease of weld inspection – determined by the type of weld and its location
- Availability of contractors – the chosen fabrication method should not unduly restrict the range of companies that are capable of fabricating the package by that method
- Experience and capability of the potential contractor companies in the chosen fabrication methods.

In designing for fabrication, the designer should aim to do the following:

- Use as few materials and components as the requirement permits
- Reduce the parts count, for example, by combining two or more parts into a single part
- Use a minimal variety of fasteners
- Use standard sections and sizes
- Make sure the design is as straightforward and economical to manufacture and maintain as possible
- Avoid manufacturing tolerances being unnecessarily restrictive.

6.2.2 Characteristics of stainless steel

Most stainless steels used for waste containers are characterised by a high work hardening rate. Austenitic stainless steels work-harden significantly during cold working. This can be both a useful property, enabling extensive forming during stretch forming without risk of premature fracture and a disadvantage, especially during machining, requiring special attention to cutting feeds and speeds.

Special care should be taken to avoid the risk of cross-contamination from other materials, such as carbon steels, but also light and lower melting point metals, and organic and inorganic materials used in cutting and forming processes, as this can seriously impair the properties of the finished containers. Segregation from other activities and cleanliness of the work areas and equipment are imperative to maintain the corrosion resistance of the finished containers. Fixtures and fittings should only be of stainless steel. Chloride contamination can have an impact on the corrosion performance of stainless steels. Appropriate measures should be taken to mitigate such risks during the fabrication process, such as the use of new tooling.

6.2.3 Cutting

The usual first operation is the cutting of materials. Appropriate techniques are:

- Sawing techniques: In using this technique, the metal should be set up to have a positive feed and ample coolant at all times to reduce glazing and work hardening of the material.
- Shearing techniques: In using this technique, there should be correct clearances and good sharp edges to avoid dragging of the material over the blades. This will also reduce the surface cracking and work hardening of the resultant cut areas. This applies not only to traditional guillotines but also to blanking, punching and piercing activities. The grouping of shear cuts adjacent to each other will increase the work hardening and as an absolute minimum there should be 1.5 times the material thickness between cuts.
- Plasma cutting: This is often used for thicker material, and special care should be taken over the use of shielding gases to reduce oxidation around the cut area, the maximum witness to which is a straw discolouration. The cut often has a taper and may require additional work to achieve a square edge. If the edges are not square, it could possibly increase distortion on welded assemblies due to the propensity of stainless steel welds to shrink.
- Waterjet cutting: This is an established alternative to plasma cutting and has the added benefit from a low heat input; as a consequence there is no HAZ. The cut shape is squarer and has a better finished tolerance. The cut appears as if it has been sandblasted and is suitable for welding unless specific weld preparations are required. This method of cutting is more expensive than laser profiling, but the extra cost can be offset by less post-cutting remediation.
- Laser profiling: This is the preferred method for thinner materials. With the new fibre laser equipment a finer and cleaner cut can be achieved, so reducing the impact around the cut edge. This technique has an added benefit of being very cost effective. Laser profiled edges are, in general, acceptable for welding without any additional operations, unless specific weld preparations are required.

6.2.4 Forming

The secondary or final forming of stainless steel results in additional work hardening of the material and should, therefore, be kept to a minimum. It is recommended that samples of the post-forming material are hardness tested using the Vickers or Rockwell technique. The results should be compared with the pre-forming material, to ascertain whether the resultant increase in hardness due to forming is acceptable. Whilst no specific hardness limits are available, it is recommended through experience of the producer and process control that suitable hardness limits are developed for the container, reflecting successful forming.

Post-forming heat treatment can restore the material back to a similar level of pre-forming hardness but should only be undertaken in a vacuum or suitable inert atmosphere, with awareness of the dimensional effects of stress relieving and the risk of oxidation or discolouration of the surface.

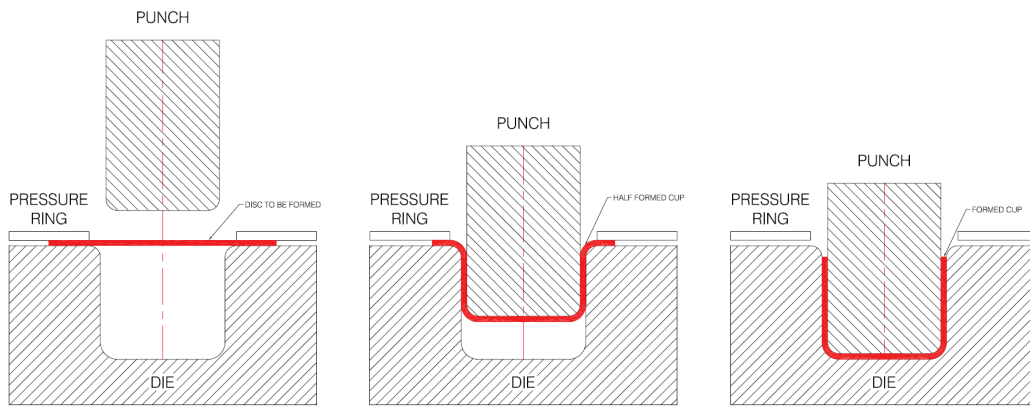
Hardened forming tools should be used at all times with the surfaces being clean, of a suitable texture and free from contamination as tooling related particles may result in undesirable surface imperfections. It should be noted that austenitic stainless steels are characteristically prone to galling and tooling 'pick-up'; as such the development of forming processes is a specialist activity that may require the presence of coatings and lubricants to achieve a desirable surface finish. Such lubricants and barriers must be removed thoroughly prior to heat treatment or the final product.

The bending of the material using normal techniques such as rolling, press-brakes, etc. will require a certain amount of over-forming as the material will recover or "spring back" a little. The radius of the corner should be controlled relative to the material thickness and the alloy designation, and the larger the radius the less work hardening occurs. If it is possible to form the material into the shape instead of welding multiple pieces together it is in general beneficial to the finished product properties, as long as the work hardening has been kept to a minimum.

The utilisation of deep drawing techniques, as illustrated in Figure 7, to form the bases and the bodies of waste containers can have benefits for the mechanical and corrosion properties of the finished waste container. The post-forming heat treatments can restore the original material properties, and if no post-forming treatments are required the material surface can form a hardened layer that enhances corrosion resistance. It is important that all tools be in a hardened condition and kept clean and well lubricated at all times. Different types of stainless steel have significantly different deep drawing properties and the residual hardness figures should always be known. The work is best undertaken in a double acting press that utilises a cushion/pressure plate to avoid the wrinkling effect of the component flange.

It is generally accepted that a punch and die radius of nominally 5 to 10 times the material thickness will allow a smooth draw in of the flat sheet. It may take several stages to achieve the final shape with inter-stage annealing to maintain the materials properties. The type of lubricant used should be chosen with care to avoid chloride contamination, which could accelerate corrosion. It follows that lubrication should be removed after forming. The high cost of the tooling can be a limiting factor for smaller quantities of waste containers, but for larger quantities of waste containers the design should be undertaken with a view to deep draw pressing if forming is required, especially with round products.

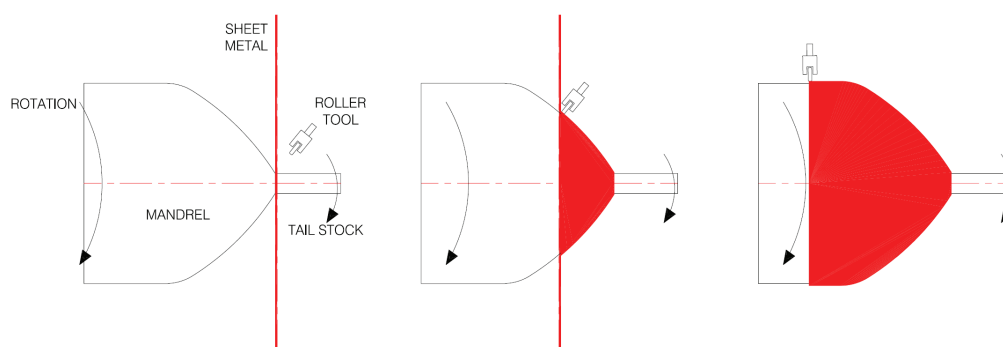
Figure 7: Illustration of the deep drawing process



It should be noted that stainless steel sheets from different producers have different characteristics within the boundaries of the product grade or supply standard. This is usually reflected in subtle variations in the mechanical and chemical properties, and underlying this, variation in the microstructure relating to grain size and grain morphology. Different manufacturers have subtle differences in heat treatments and rolling schedules/breakdowns. It should be noted that grain size and grain morphology can have a significant influence on deep drawing behaviour. The fabricator should ensure that variation in steel microstructure from batch to batch provides consistent results in the deep drawing operations.

Spin-forming, as illustrated in Figure 8 below, which involves a tool forcing the material over a mandrel, has a lower tooling cost than deep-drawing techniques, but has inherent issues with residual stresses within spun components and high work hardening characteristics. Post-forming annealing and re-working may be required to achieve the finished properties required. It may be cost effective to produce non-containment components with this method.

Figure 8: Illustration of the spin-forming process



6.2.5 Welding

The welding of stainless steel can be achieved utilising a variety of welding processes, but it should be understood that welds introduce uncertainty in the mechanical properties as the stress-strain properties of the weld and HAZ can be inconsistent. Welding can also introduce contamination into the parent material in the form of filler wire and any airborne contaminants that may be encountered in the welding area. The welded joint can be a structural and corrosion weak point if not undertaken correctly. One of the main considerations at the design stage should be to reduce the number of welds to a minimum. In general, stainless steel shrinks during the welding process and the reduction and control of this shrinkage is important as this is the cause of distortion. Wherever possible, automated welding techniques will give an even repeatable weld that will maintain a consistent output and reduce uneven shrinkage distortion. Most welding techniques can be automated with robotics to give either a semi or fully automatic system. Typical welding techniques include the following:

- MIG (metal inert gas) /MAG (metal active gas) is a process where the arc and weld pool are formed using a bare wire electrode protected by an inert gas. This is also considered more suitable for thicker plate requirements. The weld is produced by forming an arc between a consumable metal electrode and the workpiece; the electrode melts to form the weld bead which makes it easier to build up weld reinforcement and fill larger weld preparations. The finished weld will, however, require mechanical dressing to prepare for non-destructive testing (NDT) and to be crevice free.
- TIG (tungsten inert gas) welding is when an arc is formed between a non-consumable tungsten electrode and the metal being welded. Gas is fed through the torch to shield the electrode and molten weld pool. If filler wire is used, it is added to the weld pool separately. This is more suitable for thinner more delicate requirements and is more adaptive to automatic systems. Pulsing of the current will aid deeper penetration for less heat input, helping reduce distortion and the HAZ around the weld area. Emerging processes such as 'Keyhole' or 'K-TIG' take advantage of modern electronic micro processing in the welding power source to further localise or concentrate heat input for deeper penetration.
- Plasma welding is very similar to TIG welding as the arc is formed between a pointed tungsten electrode and the workpiece. However, by positioning the electrode within the body of the torch, the plasma arc can be separated from the shielding gas envelope. Plasma is then forced through a fine-bore copper nozzle which constricts the arc. This technique is considered most suitable for thicker plates which would otherwise require multi-runs and larger weld reinforcements. Pulsing of the current will aid deeper penetration for less heat input, helping reduce distortion and the heat affected zone around the weld area.

- The latest fibre laser welding system (also called deep penetration welding or keyhole laser welding) is a line-of-sight, single-sided, non-contact joining process. It is characterised by its high focused energy density, which is capable of producing high aspect ratio welds (narrow weld width: large weld depth). This can be used for both sheet and plate, and it is significantly faster than other techniques. The high temperatures achievable and faster speeds produce a narrower and deeper welding technique that reduces distortion and the size of the HAZ. It is possible to use electron beam welding (EBW) to achieve similar characteristics to a laser weld, but the component must be contained within a vacuum chamber, which typically increases the cost and complexity of the process conditions.

Post-weld heat treatment and cleaning removes the naturally occurring oxide layer from the weld that can accelerate corrosion of the material. It is also important to understand that crevices can act as a point of corrosion initiation and also accelerate corrosion. Crevices should be eliminated at the design stage, but weld profiles should also be crevice free. The aim is to restore the natural passive layer of oxide of stainless steel that aids corrosion resistance. There is a range of techniques that can be used, but cost may be a limiting factor:

- Pickling and passivation is a standard technique where pickling solutions of nitric acid (HNO_3) and hydrofluoric acid (HF) remove the scale and the underlying chromium depleted layer and restore the corrosion resistance. Common passivation treatments include nitric acid solutions or pastes which will clean the steel surface of free iron contaminants. Pickling solutions also remove contaminants such as ferrous and ferric oxide particles but cannot be totally relied upon to remove sufficient of the weld oxide layer. Additional mechanical methods such as grinding or abrading may be required prior to pickling and passivation. After the processes the components will require a thorough washing in chloride free water.
- Vaqua-blasting is a system consisting of a jet of air, water and glass beads that acts like a very fine shot blast. This removes a very fine layer of the surface material stripping away any weld oxidisation and surface contaminants. The stainless steel will naturally re-passivate afterwards. This technique also has a low level vibro-stress relieving action. The resultant surface is considered good for decontamination activities and is of a uniform finish.
- Mechanical methods such as grinding or abrading are suitable for removing larger areas of oxides and smoothing out weld crevices. Care must be taken with the choice of abrasive to ensure no chlorides are introduced into the material surface. Finer methods will give a polished surface that is easier to decontaminate but may cause micro-crevices that can accelerate corrosion during long-term storage.

Weld inspection is a critical element in ensuring the quality of the welds. Weld inspection techniques vary from a visual review of the weld for surface and fusion issues to volumetric inspection for a more detailed report of the weld. The more in-depth techniques take significantly longer to undertake and require specialist equipment and are therefore more expensive. The type of weld and the quality control requirements will determine the method of inspection. The visual inspection of welds is a pre-requisite prior to other forms of NDT. There are variants upon the ultrasonic and radiography methods than can be executed in real time as the weld is laid but again there are additional equipment costs to be considered, although these can reduce operational time. Some of the typical NDT techniques used are as follows:

- Visual inspection, with the aid of simple equipment such as metal rule, magnifying glass, straight edge, weld size gauge, set square, is often the most cost-effective method. However it must take place prior to, during and after welding and requires little equipment.
- The liquid penetrant inspection method is applicable when attempting to locate flaws open to the surface of mostly non-porous material. This method cannot identify internal flaws within the weld.
- Ultrasonic testing utilises high frequency mechanical energy, that is, sound waves, to conduct examinations and measurements on a test area. When there are discontinuities such as inclusions, porosity, cracks, etc. in the sound wave path, part of the mechanical energy will be reflected from the discontinuities' (reflectors') surfaces.
- In radiography testing the test-part is placed between the radiation source and film (or detector). The material density and thickness differences of the test-part will attenuate (that is, reduce) the penetrating radiation through interaction processes involving scattering and/or absorption. The differences in absorption are then recorded on film(s) or through an electronic means.

6.2.6 Machining

In general, the final operation in the fabrication process is to machine any areas for which specific accuracy in dimensions and surface finish will need to be achieved. This will include sealing faces, surfaces for interfacing with adjacent waste containers in stacking, surfaces for interfacing with lifting grabs or lifting frames in lifting, and areas which will need to be interfaced with plant items.

Dependent upon the shape of the waste container, for example drum-type waste container or box-type waste container, different machining techniques would be used.

When machining stainless steels it is important to ensure that there is no dwell or rubbing caused by machine vibration or tool chatter that can cause work hardening. Either high speed steel (HSS) (wrought or sintered) or cemented carbide tools can be used for machining stainless steels.

6.2.7 Manufacturing record

Providing traceability of all materials, manufacturing techniques, non-destructive testing, final record of dimensions and other relevant information is essential to allow a full lifetime record for the waste containers. It is considered standard practice to provide an individual record for each waste container, specifying evidence of all such details.

The incorporation of all the elements of materials, manufacturing techniques, and inspection and testing undertaken in a detailed quality plan, which is up to date with all the manufacturing drawings and specifications, underpins the quality assurance for the waste containers. The operational requirements of the waste container will determine the level of dimensional recording required. Remote interface areas will require either dimensional records or a proven gauge check to ensure that the required tolerance and accuracy is achieved.

6.3 Good practice in the manufacture of reinforced concrete waste containers

The following sub-sections describe good practice and guidance on the design and manufacture of reinforced concrete waste containers.

6.3.1 Design

Reinforced concrete waste containers should be designed in complete accord with a compatible set of design rules, for example, the suite of Eurocodes supplemented only with non-contradictory complementary information, for example, use of fib Model Code 2010 [40], BS 8666 [85], PD 6687 [86] and other European standards.

Codified rules should not be extrapolated beyond the stated limits. This applies to the material properties and all other aspects of the design.

The design should consider the ultimate limit state and the serviceability limit state. These limit states infer the reliability target, that is the probability of failure considering the statistical distribution of strength and load actions. Load actions associated with waste container design, that is filling, lifting and stacking, should be considered at the appropriate limit state to ensure the required performance criteria as set out elsewhere in this guide, for example maximum crack width control, are satisfied.

The design should assume parameters that are consistent with the manufacturing specification, which should be used separately to control and validate the manufactured products. The manufacturing specification is expected to be project-specific. However, criteria should meet or exceed requirements set out in the National Structural Concrete Specification for Building Construction (NSCS) [87]. Any geometrical tolerances associated with the manufacture should be considered explicitly in the design. This should include deviation of the reinforcement during concrete placement, which will be a function of the cage rigidity.

Reinforcement should be provided to all surfaces and through the thickness of the sections, with sufficient area, spacing and cover to satisfy the design requirements.

Designs should assume certified materials that have properties controlled to be in accordance with the relevant codified parameters. Material variation should be demonstrated to be in keeping with the material partial safety factors or strength reduction factors employed by the design code.

Reinforcement should be detailed in accordance with codified rules supplemented by industry good practice, for example, the Institution of Structural Engineers (IStructE) Standard Method of Detailing Structural Concrete [88].

All welding should be carried out by companies that have achieved the relevant certification from CARES or equivalent body.

All embedded items such as reinforcement couplers should be certified by CARES or equivalent body.

Bar chairs, tie wire, stools, spaces and/or any other cast in items should be of suitable material to not detrimentally impact the design performance.

6.3.2 Manufacturing strategies

There are four typical approaches for manufacturing precast elements. It is important to recognise that all aspects of design and manufacture are affected by the chosen manufacturing strategy.

The first approach, standard monolithic precast, is likely to be the most appropriate solution for a large production run of waste containers, although depending on the details of the design an alternative manufacturing approach could be proven to be a viable alternative.

The clear advantage of the first approach against the other three is that the body of the waste container is a single component, with no joint between base and walls in the other three approaches. For the other approaches to be justified, the additional joints would need to be designed such that they have no detrimental effect on waste package performance.

Approach 1 – Standard monolithic precast

In this approach, the body of the waste container can be cast upside down in a single joint-free pour. Lifting points on the bottom surface are required for de-moulding and turning. Alternatively, the mould may be installed in a turning frame.

Approach 2 – Precast with conventional construction techniques

In this approach, the base and the walls of a waste container can be cast separately using conventional techniques. For larger waste containers which cannot easily be rotated after casting if Approach 1 is used, this approach would be more appropriate. For this approach to be justified, the joint between the base and the walls will need to be carefully designed such that its integrity can be assured.

Approach 3 – Panelised solid precast

In this approach, the base and the walls are each cast flat before assembly and are then connected to form the final waste container. Again, detailing of the connections will need to be carefully considered. One clear advantage of this approach is that it is compatible with existing facilities for manufacturing precast panels (for example, automated high throughput production lines).

Approach 4 – Panelised hybrid precast

This approach is similar to Approach 3, in which the waste container is assembled from panelised solid precast components. The concrete panels, either as separate or twin-wall type panels with attached reinforcement, create two precast faces to set dimensions with the inner void being subsequently concreted. Again, detailing of the connections will need to be carefully considered, as well as the temporary support and control of movement during subsequent concreting. As for Approach 3, it is compatible with existing manufacturing facilities for manufacturing precast panels.

6.3.3 Component production

Good practice for precast concrete manufacturing is detailed in the NSCS [86], which encompasses requirements from BS EN 13670 Execution of Concrete Structures [65] and the Eurocodes.

Formwork

Formwork should be designed to BS 5975 Code of Practice for Temporary Works Procedures and the Permissible Stress Design of Falsework [89].

Best practice for batch production of waste containers would use reusable steel moulds, with collapsible cores that struck downwards. Casting the component upside down eliminates the need for joints and helps ensure good slab quality. These moulds require a slight draft angle (tapered mould walls) to enable release without causing component damage. All edges should be provided with a chamfer (typically 10 mm) to minimise damage. Inserts and embedments should be minimised in order to increase production rate. Permanent non-structural edge forms can be cast into the top face to enable pouring of the in-situ grout and top slab.

Precast components typically achieve Class F5 finish (Plain Finish), similar to Visible Structures (Class F4). The NSCS defines Plain Finish, which requires careful selection of concrete, release agent and formwork, as well as thorough concrete compaction. Pre casting facilities are able to apply a range of finishes depending on the application, so an enhanced durability finish may be specified if necessary as outlined in CS030 Formwork: A Guide to Good Practice [90].

Reinforcement

Reinforcement should be assembled into complete cages prior to casting. Prefabricated reinforcement comes in the form of welded mesh that is cut and bent to shape. Assembly using bent mesh is most efficient and accurate, but is typically limited to 12-16 mm bars and requires the use of appropriate details.

Larger diameter bars (or areas where clashing may occur with inserts (for example, corner handling assemblies)) preclude the use of bent mesh. Such areas can be fixed manually in-situ at the expense of production rate.

Concreting and curing

All concreting operations should be guided by the good practice defined in the NSCS, as already discussed above.

Concrete construction conventionally requires good quality compaction to avoid reworking, which would introduce unplanned cold joints, honeycombing (a rough, pitted surface caused by incorrect concrete mix or poor compaction) and segregation (separation of aggregates according to size, caused by poor mix or excess vibration). However, complex mould geometry or dense reinforcement may prevent “poker” (vibration tool inserted into fresh concrete) access to the bottom of the mould. Where pokers are to be used, the reinforcement must be adequately spaced to accommodate the pokers and also adequately fixed to avoid reinforcement bars being displaced by the poker. Alternatively, vibrators may be fixed directly to moulds, or self-compacting concrete may be used to avoid the need for compaction.

Mix design (including additives and release agents), curing environment (including temperature and relative humidity), and the permeability of any surface coverings and formwork chosen by the manufacture, should be reviewed by the designer to avoid detrimental effects during curing. All agents within the concrete mix must also be demonstrated to have no long-term detrimental effect on the concrete.

Handling and storage

Pre-cast units are typically lifted using cast-in steel inserts with threaded sockets or studs.

De-moulding requires lifting sockets on the base of the unit. Rotation of units could be performed with a soft sand base or a bespoke frame with cast-in turning sockets at the centre of gravity.

Stacking during transport of the units to the waste producer’s site is unlikely, although stacking during storage at a pre-casting facility is possible and consideration will need to be given to the temporary works solution to enable this.

Ideally, waste containers should be stored single height in the pre-casting facility. During storage, faces exposed in the finished condition should be protected from mechanical damage, dirt, staining, rust marks and other disfiguration.

Identification

The stainless steel identification plates needed to satisfy RWM's requirements for identification, as discussed in Section 5.5, could be used to track the units through manufacturing. Prior to these plates being fitted, steel tags may be attached to the reinforcement cages for the same purpose.

Transport

Potential impact loads during transport from the manufacturer to the waste producer may be of critical concern to the waste container designer, who should consider serviceability conditions during transport.

Geometric tolerances

Geometric tolerances for structural concrete are outlined in the NSCS and in BS EN 13670. However, pre-cast facilities are often able to work to tighter tolerances than standards intended for in-situ construction. For example, the tolerance on cover to reinforcement may be reduced from 10 mm to 5 mm, allowing designers to produce thinner structures or to reduce the risk of problematic cracking. Steel moulds can be manufactured very accurately, typically to tolerances of less than 5 mm.

For stacking performance of the completed waste package, appropriate tolerances for mating surfaces will need to be considered.

Testing and inspection

The manufacturer should operate a quality management system to BS EN ISO 9000 [91]. A comprehensive inspection and test plan (ITP) would be required for high integrity components of this type (see guidance in Annex B Guidance on Quality Management of BS EN 13670 [65]). According to the NSCS, records of unit mark, composition, date of casting, and curing regime are required for each component.

Initial prototypes should be produced to check mould accuracy and casting performance before a production run begins. First off prototypes can undergo destructive testing, according to BS EN 12390 Testing Hardened Concrete [92]. Sample cores should be taken to assess concrete compaction and compressive strength. Geometric performance can be assessed using laser scanning as best practice.

Production run components are inspected according to the ITP. Concrete properties are generally monitored for the pre-casting facility as a whole, with stringent concrete mix quality control. Critical tolerances must be monitored on each finished component.

Production and control

The concrete production plant should be accredited by a third party accreditation body, for example, Quality Scheme for Ready Mixed Concrete (QSRMC), in accordance with BS EN 206 [23].

Mixing of concrete components should be carried out according to Clause 9.8 of BS EN 206 [23], and employing a mixer conforming to Clause 9.6.2.3(a) of BS EN 206 [23]. Dry batching and continuous mixing should not be used.

The manufacturer should have its own laboratory equipped to run the necessary production and conformity control tests.

All data for checking the composition of the concrete should be available on request, either electronically or on paper.

The production plant should have sufficient capacity to ensure that the structural components may be cast without unintentional construction joints or pour lines.

Before commencement of production, initial testing of the concrete mix should be performed in accordance with Clause 9.5 and Annex A of BS EN 206 [23].

The suitability of the concrete mix should be verified with full scale trials using the constituent materials, mix design, production plant and, if required, the transport time that will be used, including change in consistence and, for air-entrained concrete, air content in connection with transport to the point of placement.

Initial testing should be repeated whenever significant changes to the constituent materials or mix design are proposed. Minor adjustments to the admixture doses to keep an even consistency and/or air content are not considered to be mix design changes.

Conformity control for compressive strength should be performed in accordance with Clause 8.2.1 of BS EN 206 [23].

Conformity control for properties other than strength, where required, should be in accordance with Clause 8.2.3.3 of BS EN 206 [23] and should include the following parameters, as appropriate:

- Water/cement or water/combination ratio
- Density
- Workability/consistence
- Air content
- Parameters related to the stability of self-compacting concrete for example, segregation resistance, viscosity, passing ability
- Durability related performance tests, for example, inverse effective carbonation resistance.

6.4 Good practice in the manufacture of DCI waste containers

The manufacture of DCI waste containers requires detailed consideration of a number of issues pertaining to aspects of the material performance, along with both the casting and machining processes. These are discussed in the following sub-sections.

6.4.1 Design of the casting

DCI containers should be designed in common with general casting best practice. In particular, as properties are significantly determined by cooling rates then a consistency of wall thickness makes a uniform casting more readily achievable. Certainly rapid changes in wall thickness, leading to transitions from thick to thin sections, should be avoided if possible. Fillet radii should be as generous as possible.

At the initial design stage the designer should be mindful of the construction of the pattern, and include appropriate features into the casting to allow for ease of pattern assembly and removal. In particular, surfaces should allow appropriate draft angles (that is, taper) to allow for pattern and mould removal. Draft-less surfaces can be achieved and may be desirable for surfaces which remain “as cast”, however these significantly add to the complexity of the mould and pattern construction and therefore consultation is needed with the foundry to determine optimum geometry.

Optimised casting stock is important if the casting is to be economically viable; while DCI is freely machined, significant levels of stock removal will increase machining time and hence have an adverse effect upon cost.

Casting simulation should be used to help design the casting and simulate the solidification process.

6.4.2 Tolerances

Waste containers are required to be stackable. Clearly the waste container will need to be designed for the stacking loads, but the means to achieve the required flatness and parallelism of the mating surfaces will also need to be considered. It is unlikely that casting tolerances will be adequate, and therefore the stacking interfaces will require accurate machining to ensure appropriate tolerances pertaining to flatness, parallelism and angularity of these surfaces are achieved.

In terms of lifting features, their size, strength, position and geometry could have significant implications for the manufacturing. This is especially so for box type (rather than drum type) DCI containers which may need to incorporate twistlock pockets for lifting. Although casting technology has developed to an extent where these may be potentially cast in-situ, which offers potential cost savings, machining post-casting may be required to obtain the required tolerances on a consistent basis.

Similarly, features of the waste containers for plant interface would typically require the waste container to locate against accurately machined hard features. Cast surfaces alone may not be sufficiently accurate, and therefore the waste container interface is likely to require machining to ensure the correct accuracy and angular alignment. Furthermore, the relative position of interfacing features to other aspects of the waste container requires consideration.

Allowances need to be made within the casting stock to allow machined features relative to casting features to be produced accurately and repeatedly. For instance, a location feature may require the waste container external surfaces to be machined accurately, and positioned relative to the lid aperture. However, the lid aperture will also have a positional relationship with respect to the inner cast surface. The design should contain sufficient stock in the casting to allow these relationships to be produced to the desired accuracy, but not so much stock as to make the machining uneconomical. To aid this process of “balancing”, or “setting” the casting for machining, it is recommended for the designer to define target datum points upon the casting. These allow the relative cast positions to be easily established by the machinist, and allow for reduced setting times leading to efficient and consistent stock removal.

6.4.3 Surface finish

A DCI waste container will usually require demonstrable ease of decontamination. However, the ease of decontamination required can vary according to the nature of the waste and customer specific needs. The most readily decontaminable finish can be achieved on a machined surface with a proven paint system, such as two part epoxy based paint processes, although the economics of machining and painting a container all-over to achieve this ease of decontamination should be reviewed. It may be appropriate, for instance, in waste containers where the waste will not require future retrieval, to leave the internal surfaces in an “as cast” state. Similarly, for certain less demanding applications, easily decontaminable surfaces can be achieved if the cast surface is suitably smooth.

6.4.4 Compliance of material properties

Perhaps the most fundamental consideration for the designer is the specification, attainment and substantiation of the waste container material properties. Material properties are a significant factor when considering impact performance, and therefore substantiation of the material characteristics is paramount to satisfying customers and regulators of the container suitability.

The initial step is to specify the desired material grade and carry out preliminary finite element analyses to determine the expected performance of the waste container under impact. Having specified the grade the next consideration is to ensure the casting complies with the required grade and associated material performance throughout production.

ISO 1083:2004 Spheroidal Cast Irons – Classification [51] defines the grades and the corresponding requirements for spheroidal cast irons. It specifies a classification based on mechanical properties measured using machined test pieces prepared from separately cast samples, cast on samples, or samples cut from a casting.

Typically castings for commercial applications will utilise either separately cast samples or cast on samples upon the waste container. These are then machined into test specimens that are tested for mechanical properties such as tensile strength and percentage elongation. Depending on the casting size and complexity this approach may not be acceptable to a nuclear regulator or customer, as the samples may not be considered truly representative of the casting as a whole; in particular, the wall thickness can have a significant bearing upon material performance.

Therefore in circumstances where additional substantiation may be required, it may be sensible to cut samples from the casting. As such, the designer may need to design in a suitable sacrificial section to allow a sample to be removed without prejudicing the performance of the component. The position of the sample should be chosen so that it is either demonstrably representative, or can be considered to be the worst case from a material performance perspective.

As material performance is strongly linked to the process control during cooling of the casting, a cooling simulation can assist in highlighting areas of the casting likely to exhibit minimum material performances.

In practice a designer is likely to initially specify a combination of cast on, cast off and samples cut from the casting so that a consistency of material properties can be demonstrated both throughout the container geometry and across each container in a batch. As this consistency is demonstrated, and the casting process matures, the rate and method of sampling potentially may be optimised to produce more economical castings.

6.4.5 Casting – first article

Due to the complexities of the geometry, and in particular the substantiation of material properties as described above, it is good practice to produce an initial casting prototype, referred to as a first article.

Initially the prototype can be used to establish that the correct geometry is being achieved. Following dimensional inspection, best practice is to then cut up this initial casting into a large number of samples. These samples can then be utilised to establish that the mechanical properties, chemical composition and metallurgy are as specified, and are consistent throughout the container.

Further consideration should be given to utilising a number of these samples for high strain rate “dynamic” testing of material properties to allow more direct evaluation against the predicted finite element simulation.

In high-volume, high-integrity castings, this destructive examination may be repeated at routine intervals throughout the casting batches, and also at the end of a batch, a last article inspection.

Practically, it is considered unlikely that such an intensive inspection regime will be required for DCI containers as they are likely to be produced in much smaller numbers than typical commercial applications.

Furthermore, the very nature of these containers is that they are structurally very strong with large reserve factors under benign normal operating conditions, commonly referred to as massive and passive structures within safety engineering terminology. Therefore it is considered that a casting substantiation program could be developed to regulatory satisfaction which builds upon the initial first article inspection, and proves that casting properties meet those predicted in the thermal simulation modelling. The properties could then be tested, and shown to be acceptable against the properties assumed within the finite element impact model. At this point, it is then a question of frequency and method of sampling. If the first article inspection demonstrated uniformity between cored samples from the container and cast on coupons, then it is considered that the optimum approach in production would be routine inspection of cast on coupons with batch sampling of cored out test pieces.

If any deviation were subsequently discovered, the destructive inspection of a container could be repeated and compared back to the initial first article results to ascertain any drift in the process.

To optimise manufacturing efficiency, the ultimate desire is to move to a regime of strict control of the casting process to ensure product quality, rather than invasive inspection of each container.

6.4.6 Casting – production

It may be that the first article process as described above is repeated until the casting achieves the desired form and consistency. However, once this has been demonstrated then the production programme can be commenced. At this stage, the emphasis moves onto more routine quality control and assurance, with appropriate arrangements established to capture the conformance of the casting geometry, surface finish and material properties.

At the casting stage it is common to carry out post-casting NDT in the form of ultrasound testing; detailed guidance is provided within BS EN 12680-3:2011 Founding – Ultrasonic Examination [93]. This inspection methodology can be utilised by suitably qualified and experienced operatives to detect internal casting flaws and voids, typically porosity caused by sub-optimal cooling.

At the casting stage, magnetic particle inspection (MPI) is often not carried out, particularly as this only detects surface and very near-surface defects and so is not appropriate for stock surfaces which are subsequently machined. However, there may be circumstances where MPI is specified, such as areas impractical to successfully ultrasound, or where surfaces may be left in the as cast condition. Detailed guidance is provided within BS EN 1369:2012 Founding – Magnetic Particle Inspection [94].

6.4.7 Machining

Once a casting process is mature, and tolerances proven to be consistent, the moulds and patterns may be adjusted to produce near net shape castings which optimise the amount of machining.

It is usual for foundries to cast trunnions onto DCI containers purely for the purpose of handling within the foundry, noting that these castings typically weigh 5-40 tonnes. These features can present a problem for a machinist in terms of the amount of material to be removed, along with the fact that once removed, the handling features can no longer be utilised during production. Therefore, the designer should consult with the machinist, and if necessary provide features which allow for lifting and manipulation of the casting during machining operations.

DCI is free-machining as for most steels, and therefore tolerances and finishes are typically attained as per large machined steel components. In particular, with appropriate tooling, surface roughness values (Ra) of between 1.6 and 0.8 μm can be achieved for seal faces with standard machining processes.

It is not usual to repeat ultrasonic testing at the machining stage, other than where cast on items such as trunnions may have prevented meaningful testing during casing. It is common to carry out MPI on all accessible surfaces of the container. The designer will need to specify acceptable flaw sizes and locations as directed by the MPI standard, and these should principally be based on appropriate fracture mechanics analysis of the material and expected loads from impact analysis.

6.4.8 Surface protection

It is likely that the container will require surface protection to protect against corrosion. The required surface preparation is described within BS 7079:2009 [95], noting that typically methods for steel substrate preparation can equally be utilised for DCI.

The selection of an appropriate paint system can be a complex undertaking and is dependent upon many factors, often directed by customer specifications. Provided that the appropriate surface preparation has been carried out, similar paint finishes to large steel components can be attained. BS EN ISO 4618:2006 [96] provides further detailed guidance.

7. Use of codes and standards in waste container design

Wherever possible, waste containers should be designed, manufactured, constructed, quality assured, tested, inspected and maintained to appropriate codes and standards. Typically, these established codes and standards refer to British Standards, ISO standards, Eurocodes, ACI and ASME codes, and include specifications of materials and standard component details (for example, screw thread).

Since no codes and standards have been developed specifically for the design and manufacture of waste containers, the present document has been developed to define good practice and to provide guidance to help the designer arrive at waste container designs that are “fit for purpose”.

Various organisations have produced guidance documents (for example, technical assessment guides, regulatory guides, good practice guides) on various aspects of the design, manufacture, construction, quality assurance, testing, inspection and maintenance of waste packages for the transport, storage and disposal of radioactive materials. A selection of such guidance documents is listed in Appendix A. Where appropriate, these guidance documents should be consulted.

The process of drafting codes, standards and guidance documents brings together the collective expertise of specialists and stakeholders from purchasers, suppliers, practitioners and researchers, and the resulting documents represent good practice and have a certain level of authority. The process of revision of codes and standards ensures that the latest knowledge is incorporated and that continuous improvements are made.

Since no codes or standards exist for the structural design of waste containers, either in terms of stacking design and handling (lifting and tie-down) design, or on containment and filling design, appropriate established codes and standards for the design of similar structural components using similar materials with similar safety significance should be adopted. Judgement is required as to what is an appropriate code and standard that could be adopted and must be made on a case-by-case basis.

Whenever it is necessary to use different codes and standards for different aspects of the same item, the compatibility between these codes and standards should be demonstrated. The combining of different codes and standards for a single aspect of a structure should be avoided. Where this cannot be avoided, the combining of the codes and standards should be justified and their mutual compatibility demonstrated.

While the structural design of a waste container should be based on appropriate codes and standards, designing for impact performance and fire performance typically cannot be dependent on any code or standard. The design should be based on a combination of experience, tests and analyses, to demonstrate that the performance of the structure satisfies the performance criteria.

8. Use of calculations in waste container design

While the performance of a waste package or waste container against a number of the requirements specified in the WPS can be verified by simple measurements or pass/fail judgment, its performance against other requirements including structural performance in handling and stacking, as well as the thermal, shielding, criticality, and impact performance, will need to be demonstrated by more involved means. These performance requirements can be substantiated by a combination of physical testing, calculations and reasoned argument.

Calculations are essentially mathematical models of reality, and could range from hand calculations to computer analysis (for example, finite element analyses). Physical testing may be used on its own, but often needs to be supplemented by calculations and computer simulation, to help interpret the results and provide a complete understanding of the behaviour. Reasoned argument should be used in all cases to interpret the results of the physical tests and calculations, to provide the cohesion to the substantiation, whether the substantiation is by testing or calculation or a combination of both. Good practice in calculations in general is discussed in the following subsections. The good practice guidance for impact analyses, TCSC 1087 [77], and for thermal analyses, TCSC 1093 [97], should be consulted for industry good practice in these two areas.

To produce sound calculations of any kind, attention must be paid to the calculation method, assumptions, input data, interpretation of the results and checking.

8.1 Calculation method

Any calculation method used must be appropriate. All calculations are essentially mathematical models of real situations, involving simplifying a real situation so that it is amenable to the specific calculation method. The calculation method must be understood and it must be appropriate to the situation to which it is being applied.

If the calculation is for assessing a specific aspect of the design of a waste container against a specific design code or standard, then the specific requirements for the calculations as specified in the code or standard must be adhered to.

8.2 Assumptions

All calculation methods involve assumptions. It is important that the assumptions, implicit or explicit, in a calculation method are known and understood, and they must be reasonable and justified for the situation for which the calculations are applied to.

In order to make a situation amenable to calculation, geometries, loadings, material properties and boundary conditions often also need to be simplified. Such simplifying assumptions must be justified.

If there are uncertainties in the accuracy of the assumptions, assumptions should be chosen to achieve a conservative solution.

8.3 Input data

The input data used must be valid and appropriate for the situation being calculated, and consistent with the calculation method and the code and standard being used.

Where uncertainty in the input data exists, or if certain parameters could vary in reality and a range of values are possible, appropriate margins and bounding values should be used to take account of the potential variation.

Extrapolation of data beyond the range for which they are documented should not be undertaken without good justification.

8.4 Interpretation of results

Results must be interpreted taking into account the assumptions of the calculation method, the simplifications used to represent the situation being calculated, and also the nature of the input data. It is important to not conclude more from the calculation than is justified.

8.5 Checking

All calculations must be thoroughly checked. Checking should be carried out by the person who carried out the calculations, by others in calculations team, and by experts who are not involved in the work. Results of the checking should be thoroughly documented.

9. Design and manufacturing information requirements

Each waste packager needs to ensure that their arrangements for data and information recording comply with the relevant RWM specification [98]. Such arrangements should be agreed with RWM prior to the start of the activities to which they relate. However, in terms of container design this is often not the case. Information recording requirements are considered as part of disposability assessments, so are principally discussed with RWM at that stage, when design work may be largely complete, though manufacture may not be.

Waste container designers therefore need to ensure that they keep full and comprehensive records of design information, and relevant manufacturing information. Similarly, those ordering containers need to ensure that the procurement specification includes all the relevant standards applying and the quality documentation to be provided.

The waste packager's management arrangements to ensure that such information is requested should comply with the relevant RWM specification [99].

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Appendix A

List of codes, standards, guidance and other relevant documents

This appendix lists codes, standards, guidance and other documents that are relevant to one or more aspects of the design and manufacture of waste containers.

The list is organised into the following headings:

1. Design – general, where a document is relevant to one or more aspects of design and manufacturing, or is relevant for the design and manufacture of more than one type of containers
2. Documents relevant to the design and manufacture of stainless steel containers
3. Documents relevant to the design and manufacture of reinforced concrete containers
4. Documents relevant to the design and manufacture of DCI containers.

Note that under headings 2 and 3, the documents are further grouped under appropriate sub-headings.

The documents listed under each of the headings are arranged in alphabetical order by title.

The list does not include regulations or waste package specifications, and the documents are limited to UK or European documents, unless a particular non-UK or non-European document is especially relevant.

It is important to note that codes, standards and guidance documents are typically reviewed and revised on a regular basis, and the reader is therefore advised to check that they are using the latest published version of these documents.

Author	Reference	Title	Description
1. Design – General			
International Atomic Energy Agency	SSG-26, 2014	Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2012 Edition)	This document provides recommendations and guidance on achieving and demonstrating compliance with IAEA Transport Regulations, which establishes the requirements to be applied to the national and international transport of radioactive material.
Office for Nuclear Regulation	DFT/RMTD/0004 2005	An Applicant’s Guide to the suitability of elastomeric seal materials for use in radioactive material transport packages,	This guide summarises the material, environment and geometry characteristics of elastomeric seals to assist applicants for UK competent authority approval of transport packages in the selection and justification of elastomeric seals.
British Standards Institution	PD 6687-1: 2010	Background paper to the National Annexes to BS EN 1992-1 and BS EN 1992-3	The Eurocodes are a series of 10 European Standards, EN 1990 - EN 1999, providing a common approach for the design of buildings and other civil engineering works, and construction products. When there is a need for guidance on a subject that is not covered by the Eurocode, a country can publish complementary information that supports the Eurocode. This PD contains complementary information to support BS EN 1992-1-1:2004, BS EN 1992-1-2:2004, and BS EN 1992-3:2006.
British Standards Institution	BS EN 1990:2002	Basis of structural design	This standard is the head document in the Eurocodes suite. It describes the principles and requirements for safety, serviceability and durability of structures, the basis for their design and verification, and gives guidelines for related aspects of structural reliability.
Transport Container Standardisation Committee	TCSC 1080, 2010	Finishing systems for transport containers	This TCSC document provides guidance on the specification and application of coating systems to a range of commonly encountered surfaces.
Transport Container Standardisation Committee	TCSC 1086, 2009	Good practice guide to drop testing of Type B transport packages	This TCSC document provides complementary guidance to the “Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material” (TS-G-1.1) on the technical aspects of drop testing.
Transport Container Standardisation Committee	TCSC 1093, 2012	Good practice guide to thermal analysis and testing of transport packages	This TCSC document provides guidance on the thermal testing and analysis of packages, to supplement and support the information provided in the IAEA Transport Regulations and the accompanying advisory material.
British Standards Institution	BS 3580:1964	Guide to design considerations upon the strength of screw threads	This standard provides guidance on the design of screw threads.

Author	Reference	Title	Description
Serco	SERCO/ 005084/ 001, Issue 1, December 2011	Implications of RWMD 500 year waste container integrity target compared with 150 years for container design and cost	This report assesses a number of current designs (as of 2011) of waste containers as to whether they will maintain their integrity over a 500 year period and, if not, what modifications are required and what are the cost implications. This report contains useful discussions on degradation mechanisms of a range of materials used in the manufacturing of waste containers.
British Standards Institution	BS 3643- 1:2007	ISO metric screw threads. Principles and basic data	This standard gives a compilation of principles and basic data for single-start, parallel screw threads having the ISO basic profile for triangular screw threads.
British Standards Institution	BS 3643- 2:2007	ISO metric screw threads. Specification for selected limits of size	This standard specifies the fundamental deviations, tolerances and limits of size for a range of tolerance classes for coarse pitch, fine pitch and constant pitch ISO metric screw threads.
British Standards Institution	BS EN ISO 4762:2004	Hexagon socket head cap screws	This standard specifies the characteristics of hexagon socket head cap screws.
Transport Container Standardisation Committee	TCSC 1079, 2013	Lifting Points for radioactive material transport packages	This TCSC document makes recommendations on the design, testing, examination and marking of lifting points for radioactive material transport packages. The code defines the recommended design criteria and minimum safety factors for lifting points, which includes methods for designing specific handling features such as lugs and trunnions.
Arup/RWM	Doc Ref 69760-15-1, Issue 1, June 2009	Proposed holistic methodology for assessing waste package impact performance.	This document defines the methodology, based on a combination of finite element analysis and material breakup tests, for the assessment of the impact performance of waste packages.
British Standards Institution	BS EN ISO 9000:2015	Quality management systems. Fundamentals and vocabulary.	This standard describes the fundamental concepts and principles of quality management.
British Standards Institution	BS 2573- 1:1983	Rules for the design of cranes: specification for classification, stress calculations and design criteria for structures,	This standard defines the rules for the design of cranes and it discusses classification of cranes, load combinations, selection of steel, design for stresses in components and connections, and design for fluctuating loads. It is applicable in the design of lifting and tie down points of waste containers.
Health and Safety Executive	L122 Second Edition, 2014	Safety of pressure systems - Pressure Systems Safety Regulations 2000,	The Pressure Systems Safety Regulations 2000 (PSSR) cover the safe design and use of pressure systems. The aim of PSSR is to prevent serious injury from the hazard of stored energy (pressure) as a result of the failure of a pressure system or one of its component parts.

Author	Reference	Title	Description
British Standards Institution	PD5500:2018	Specification for unfired fusion welded pressure vessels	This Published Document (PD) is the latest specification for unfired fusion welded pressure vessels.
Transport Container Standardisation Committee	TCSC 1087, 2018	The application of finite element analysis to demonstrate impact performance of transport package designs	This document sets out good practice in the use of explicit finite element method in the analysis of transport packages in impact accident scenarios. Although it was written for the analyses of transport packages, it is also relevant to the analysis of waste packages in impact scenarios.
Transport Container Standardisation Committee	TCSC 1006, 2018	The securing / retention of radioactive material packages on conveyances	This TCSC document discusses the main requirements governing tie downs, provides design criteria for various modes of transport, illustrates typical tie down systems and makes recommendations regarding operation and inspection.

2. Documents relevant to the design and manufacture of stainless steel containers

2.1. Design

TWI/Nirex	TWI Report No.13451/1/02; Nirex Ref. No.#388940	Best practice guide - Welded joint design and manufacture for stainless steel containers	This document, prepared by TWI for Nirex, provides guidance on the good practice for welded joint design and manufacture for stainless steel waste containers. It covers material, design features, welded joint design, manufacture, inspection and testing, and quality assurance.
British Standards Institution	BS EN 1993	Eurocode 3: Design of steel structures	<p>Eurocode 3 applies to the design of buildings and other civil engineering works in steel. It complies with the principles and requirements for the safety and serviceability of structures, the basis of their design and verification that are given in EN 1990 – Basis of structural design. Eurocode 3 is concerned with requirements for resistance, serviceability, durability and fire resistance of steel structures.</p> <p>It is wider in scope than most of the other design Eurocodes due to the diversity of steel structures, the need to cover both bolted and welded joints and the possible slenderness of construction. It has 20 parts covering common rules, fire design, bridges, buildings, tanks, silos, pipelined piling, crane supported structures, towers and masts, chimneys, etc.</p>
Outokumpu	11th edition 2015	Outokumpu Corrosion Handbook	This handbook addresses a wide spectrum of corrosion related issues with articles and technical descriptions covering different industrial sectors.

Author	Reference	Title	Description
Transport Container Standardisation Committee	TCSC 1088, 2016	Surface finish guide for transport containers manufactured from stainless steel	This document provides guidance on surface finish for transport containers manufactured in stainless steel. It covers classification of stainless steels, surface finish and decontamination, surface texture, standard finishes, surface treatment, correlation between surface finish and particulate retention, corrosion control, and choice of surface finish.
2.2. Material			
British Standards Institution	BS EN 10021:2006	General technical delivery conditions for steel products	This standard specifies the general technical delivery conditions for all steel products covered by BS EN 10079 with the exception of steel castings and powder metallurgical products.
British Standards Institution	BS EN 10088-1:2014	Stainless steels – Part 1: List of stainless steels	This standard, a part of the BS EN 10088 series, lists the chemical compositions of stainless steels, which are sub-divided in accordance with their main properties into corrosion resisting steels, heat resisting steels and creep resisting steels.
British Standards Institution	BS EN 10088-2:2014	Stainless steels – Part 2: Technical delivery conditions for sheet/plate and stripe of corrosion resisting steels for general purposes	This standard, a part of the BS EN 10088 series, specifies the technical delivery conditions for hot or cold rolled sheet/plate, and strip of standard grades and special grades of corrosion resisting stainless steels for general purposes.
2.3. Welding consumables			
British Standards Institution	BS EN ISO 3581:2016	Welding consumables. Covered electrodes for manual metal arc welding of stainless and heat-resisting steels. Classification	This standard provides a classification system for manual metal arc welding consumables for the welding of heat resisting and stainless steels.
British Standards Institution	BS EN ISO 17633:2018	Welding consumables. Tubular cored electrodes and rods for gas shielded and non-gas shielded metal arc welding of stainless and heat-resisting steels. Classification	This standard provides a classification system for tubular cored electrodes and rods for gas shielded and non-gas shielded metal arc welding of stainless and heat-resisting steels.
British Standards Institution	BS EN ISO 14343:2017	Welding consumables. Wire electrodes, strip electrodes, wires and rods for fusion welding of stainless and heat resisting steels. Classification.	This standard specifies the requirements for the classification of wire electrodes, strip electrodes, wires and rods for various types of welding. It covers gas-shielded metal arc welding, gas tungsten arc welding, plasma arc welding, submerged arc welding, electroslag welding and laser beam welding of stainless and heat-resisting steels.

Author	Reference	Title	Description
2.4. Welding			
British Standards Institution	BS EN ISO 9606 1:2017	Qualification testing of welders. Fusion welding. Part 1: Steels	This standards sets out the requirements for the qualification testing of welders.
British Standards Institution	BS EN ISO 3834 1:2005	Quality requirements for fusion welding of metallic materials. Criteria for the selection of the appropriate level of quality requirements	This standard provides a general outline of BS EN ISO 3834 and the criteria to be taken into account for the selection of the appropriate level of quality requirements for fusion welding of metallic materials. It applies to manufacturing, both in workshops and at field installation sites.
British Standards Institution	BS EN ISO 3834 2:2005	Quality requirements for fusion welding of metallic materials. Part 2: Comprehensive quality requirements	This standard defines comprehensive quality requirements for fusion welding of metallic materials both in workshops and at field installation sites.
British Standards Institution	BS EN ISO 15613:2004	Specification and qualification of welding procedures for metallic materials. Qualification based on pre-production welding test	This standard specifies how a preliminary welding procedure specification is qualified based on pre-production welding tests.
British Standards Institution	BS EN ISO 15609 1:2004	Specification and qualification of welding procedures for metallic materials. Welding procedure specification. Part 1: Arc welding	This standard specifies the requirements for the content of welding procedure specifications for arc welding processes.
British Standards Institution	BS EN ISO 15614 1:2017	Specification and qualification of welding procedures for metallic materials. Welding procedure test. Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys	This standard specifies how a preliminary welding procedure specification is qualified by welding procedure tests.
British Standards Institution	BS EN 1011-3:2000	Welding. Recommendations for welding metallic materials. Part 3: Arc welding of stainless steels	This standard gives general recommendations for the fusion welding of stainless steels.
2.5. Testing of welds			
British Standards Institution	BS EN ISO 17635:2016	Non-destructive testing of welds. General rules for metallic materials.	This standard sets out the general rules for the non-destructive testing of metallic materials including welds.
British Standards Institution	BS EN ISO 17638:2016	Non-destructive testing of welds. Magnetic particle testing.	The standard sets out the requirements for magnetic particles inspection of fusion welded joints.

Author	Reference	Title	Description
British Standards Institution	BS EN ISO 17636 2:2013	Non-destructive testing of welds. Radiographic testing. Part 2: X- and gamma-ray techniques with digital detectors.	This standard specifies the fundamental techniques of radiography with the object of enabling satisfactory and repeatable results to be obtained economically.
British Standards Institution	BS EN ISO 17640:2017	Non-destructive testing of welds. Ultrasonic testing. Techniques, testing levels, and assessment.	This standard sets out the recommendations for manual ultrasonic testing of fusion-welded joints in metallic materials thicker than or equal to 8 mm.
British Standards Institution	BS EN ISO 17637:2016	Non-destructive testing of welds. Visual testing of fusion-welded joints.	This standard sets out the requirements for the visual inspection of fusion welded joints.
British Standards Institution	BS EN ISO 3452 1:2013	Non-destructive testing. Penetrant testing. Part 1: General principles	This standard sets out the general principles for dye penetrant inspection that would be suitable for enhanced surface inspection of non-magnetic materials.
British Standards Institution	BS EN ISO 5817:2014	Welding. Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded). Quality levels for imperfections	This standard provides quality levels of imperfections in fusion-welded joints. It applies to material thickness greater than 0.5 mm and covers fully penetrated butt welds and all fillet welds.

3. Documents relevant to the design and manufacture of reinforced concrete containers

3.1. Design

British Standards Institution	BS EN 1992	Eurocode 2: Design of concrete structures	<p>Eurocode 2 applies to the design of buildings and other civil engineering works in plain, reinforced and prestressed concrete. It complies with the principles and requirements for the safety and serviceability of structures, the basis of their design and verification that are given in EN 1990: Basis of structural design. Eurocode 2 is concerned with the requirements for resistance, serviceability, durability and fire resistance of concrete structures.</p> <p>Part 1.1 gives a general basis for the design of structures in plain, reinforced and prestressed concrete, while Part 1.2 deals with the design of concrete structures for the accidental situation of fire exposure. Part 2 gives a general basis for the design and detailing of bridges in reinforced and prestressed concrete. Finally, Part 3 covers additional rules for the design of concrete structures for the containment of liquids or granular solids and other liquid retaining structures.</p>
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Author	Reference	Title	Description
ERMCO Publication		The European Guidelines for Self-Compacting Concrete: Specification, production and use	This is a state-of-the-art document on the use of self-compacting concrete. It covers the engineering properties of self-compacting concrete, specifying self-compacting concrete for ready-mixed and site mixed concrete, constituent materials, mix composition, production of site-mixed and ready-mixed self-compacting concrete, site requirements and preparation, placing and finishing, use of self-compacting concrete for pre-cast concrete products, and appearance and surface finishes.
Fédération internationale du béton	fib MC 2010	The fib Model Code for concrete structures	This publication presents new developments and ideas with regard to concrete structures and structural materials, and is intended to serve as a basis for future codes for concrete structures. It presents new developments with regard to concrete structures and structural materials. It covers, basic principles, principles of structural design, materials, interface characteristics, design, construction, conservation and dismantlement.
Deutscher Ausschuss für Stahlbeton	November 2012	DAfStb Guideline. Steel fibre reinforced concrete. Additions and changes to DIN EN 1992-1-1 in conjunction with. DIN EN 1992-1-1/NA.	<p>The guideline regulates the properties and applications of the material “steel fibre reinforced concrete” that are not covered by:</p> <ul style="list-style-type: none"> — DIN EN 1992-1-1 in conjunction with DIN EN 1992-1-1/NA (Eurocode 2) — DIN EN 206-1 in conjunction with DIN 1045-2 <p>and</p> <ul style="list-style-type: none"> — DIN EN 13670 in conjunction with DIN 1045-3 <p>or</p> <ul style="list-style-type: none"> — the DAfStb guidelines on concrete exposed to water-contaminating substances <p>or</p> <ul style="list-style-type: none"> — the DAfStb guidelines on concrete structures that are impermeable to water. <p>The use of steel fibre reinforced concrete is provided for in both of the above guidelines.</p>

Author	Reference	Title	Description
3.2. Concrete specification and testing			
British Standards Institution	BS EN 934-1:2008	Admixtures for concrete, mortar and grout. Common requirements	This standard defines common requirements for chemical admixtures used in concrete.
British Standards Institution	BS EN 934-2:2009+A1:2012	Admixtures for concrete, mortar and grout. Concrete admixtures - Definitions, requirements, conformity, marking and labelling	This standard specifies admixtures for plain, reinforced and prestressed concrete which are used in site-mixed concrete, ready-mixed concrete and precast concrete.
British Standards Institution	PD 6682-1:2009+A1:2013	Aggregates. Aggregates for concrete - Guidance on the use of BS EN 12620 (+A1:2013)	This Published Document (PD) gives guidance on the use of BS EN 12620:2002+A1:2008, which specifies the properties of the aggregates and fillers obtained by processing natural, manufactured or recycled materials and mixtures of aggregates for use in concrete.
British Standards Institution	BS EN 12620:2002+A1:2008	Aggregates for concrete	This standard specifies the properties of aggregates and fillers obtained by processing natural, manufactured or recycled materials.
British Standards Institution	BS EN 197-1:2011	Cement. Composition, specifications and conformity criteria for common cements	This standard provides specifications of 27 common cement products and their constituents, including conformity criteria and related rules.
British Standards Institution	BS 8500-1:2015+A1:2016	Concrete - complementary British Standard to BS EN 206. Method of specifying and guidance for the specifier.	This specification describes several methods of specifying designated, prescribed and proprietary concrete and gives guidance for the specifier on selection. It provides UK national provisions where required or permitted by BS EN 206. It also covers materials, methods of testing and procedures that are outside the scope of BS EN 206 but within national experience.
British Standards Institution	BS 8500 2:2015+A1:2016	Concrete - complementary British Standard to BS EN 206. Specification for constituent materials and concrete	This standard specifies constituent materials and concrete and gives the UK national provisions where required or permitted by BS EN 206. It also covers test methods and procedures that are outside the scope of BS EN 206, but within national experience.
British Standards Institution	BS EN 206:2013+A1:2016	Concrete. Specification, performance, production and conformity	This standard defines the tasks involved in specifying, producing and using concrete. It is intended to be used in conjunction with the complementary standards BS 8500-1 and BS 8500-2.
British Standards Institution	BS EN 14889-1:2006	Fibres for concrete. Steel fibres - Definitions, specifications and conformity	This standard specifies the requirement on steel fibres for structural or non-structural use in concrete, mortar and grout.

Author	Reference	Title	Description
British Standards Institution	BS EN 450-1:2012	Fly ash for concrete. Definition, specifications and conformity criteria	This standard specifies requirements for the chemical and physical properties as well as quality control procedures for siliceous fly ash, for use as a type II addition for production of concrete conforming to BS EN 206-1.
British Standards Institution	BS EN 15167-1:2006	Ground granulated blast furnace slag for use in concrete, mortar and grout - definitions, specifications and conformity criteria	This standard specifies the chemical properties, physical properties and durability requirements for ground granulated blast furnace slag used in the production of concrete, mortars and grout.
NDA	WPS/926/01, 2017	Guidance on the use of polycarboxylate ether superplasticisers for packaging low heat generating wastes	This guidance provides advice on the use of superplasticisers for the packaging of LHGW in order to assist waste packagers in the development of packaging strategies. Its principal aims are to inform waste packagers of RWM's current view on the use of superplasticisers in light of the current state of knowledge (as of December 2015) of their impact on complexation with radionuclides in the context of the post-closure performance of a GDF, discuss the superplasticisers that can be accepted for use by waste packagers and discuss the controls on the use of these superplasticisers.
British Standards Institution	BS EN 1008:2002	Mixing water for concrete - Specification for sampling, testing and assessing the suitability of water, including water recovered from processes in the concrete industry, as mixing water for concrete	This standard specifies the requirements for water that is suitable for making concrete that conforms to EN 206-1 and describes methods for assessing its suitability.
The Concrete Centre	4th edition, April 2010	National Structural Concrete Specification for building construction	This document aims to address the wide and inconsistent approach by UK consulting engineers to concrete frame specifications, as well as the ambiguity in specification and interpretation of concrete finishes. The specification is divided into two parts Part one identifies clauses for standard concrete construction, ensuring that all parties involved - clients, designers and frame contractors - fully understand the normal requirements of efficient concrete construction. Part two provides a clear and separate statement of the specific requirements for individual projects.

Author	Reference	Title	Description
The Concrete Society	Concrete Society TR31 2008	Permeability testing of site concrete	This standard describes the mechanisms, definitions and units used for testing the permeability of concrete. It details in-situ tests and laboratory tests applied to samples taken from site. It discusses water absorption, gas permeability, pressure-induced flow (liquids and gases), and diffusion (gas, water vapour and ionic). It provides results from case histories of site-cast concrete.
British Standards Institution	PD CEN/TR 15739:2008	Precast concrete products. Concrete finishes. Identification,	This document gives guidelines for the surface appearance of precast concrete products and the methods for inspecting and assessing the conformity of appearance for use in conjunction with specific product standards.
British Standards Institution	BS EN 13263-1:2005 +A1:2009	Silica fume for concrete - Part 1: Definitions, requirements and conformity criteria	This standard specifies requirements for the chemical and physical properties and quality control procedures for silica fume for use as a type II addition in the production of concrete conforming to BS EN 206-1.
The Institution of Structural Engineers	3rd edition, June 2006	Standard method of detailing structural concrete - A manual for best practice	This publication provides good practice guidance on the detailing of structural concrete.
British Standards Institution	BS EN 12350	Testing fresh concrete	Currently EN 12350 consists of 12 parts describing the procedures and test methods involved with sampling and testing concrete in the fresh state.
British Standards Institution	BS EN 12390	Testing hardened concrete	Currently EN 12390 consists of 12 parts describing the procedures involved in the making, curing and testing of specimens for compressive, flexural and tensile splitting strength, and the determination of other properties such as density of hardened concrete (part 7), depth of penetration of water under pressure (part 8) and elastic modulus in compression (part 13).
International Organization for Standardization	ISO 1920-8:2009	Testing of concrete. Determination of the drying shrinkage of concrete for samples prepared in the field or in the laboratory	This standard specifies a method for determining the length changes of concrete specimens due to drying in air, and the method of preparing and curing the concrete specimens to be tested.
British Standards Institution	BS EN 14651:2005 +A1:2007	Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual)	This standard specifies a method for measuring the flexural tensile (3-point bending) strength of steel fibre reinforced concrete on a moulded test specimen. The method determines the limit of proportionality and a set of residual flexural tensile strength values. It is intended for metallic fibres no longer than 60 mm. Other tests methods include <i>DAfStb Richtlinie Stahlfaserbeton</i> (4-point bending) and <i>RILEM TC 162-TDF</i> (3-point bending).

Author	Reference	Title	Description
3.3. Durability related procedures and tests			
BRE	BRE Digest 330 (2004)	Alkali-silica in concrete	Part 1 gives the background to the detailed and simplified guidance contained in Parts 2 and 4. Part 2 gives detailed guidance for minimising the risk of damaging alkali-silica reactions in new construction. Part 3 gives worked examples. Part 4 gives simplified guidance for new construction using aggregates of normal reactivity.
BRE	BRE IP 11/01 (2001)	Delayed ettringite formation: in-situ concrete	This Information Paper (IP), which is mainly concerned with in-situ concrete, identifies the circumstances in which delayed ettringite formation may cause problems
International Organization for Standardization	ISO 16204:2012	Durability – Service life design of concrete structures	This standard specifies principles and recommends procedures for the verification of the durability of concrete structures due to environmental actions causing material deterioration and due to “self-ageing”.
CIRIA	CIRIA C660 (2007)	Early age thermal crack control in concrete	This guide provides a method for estimating the magnitude of the crack-inducing strain and the risk of cracking, and, where cracking is predicted, guidance is provided on the design of reinforcement to control crack widths. For specific situations where cracking should be avoided, or where the use of reinforcement to achieve acceptable crack widths is uneconomic or impractical, measures are described to minimise the risk, including selection of materials and mix design, planning pour sizes and construction sequence, the use of insulation to reduce thermal gradients, the use of movement joints, and cooling of the concrete either prior to placing or in situ.
BRE	BRE IP 01/02 (2002)	Minimising the risk of alkali silica reaction: alternative methods	This document provides guidance on alternative methods of minimising the risk of Alkali Silica Reaction (ASR) in concrete. It supplements the guidance given in BS 5328-2, BRE Digest 330 and Concrete Society Technical Report 30 (TR30).
Bundesanstalt für Materialforschung und -prüfung (BAM)	(2013)	Non-destructive testing of nuclear power plant concrete structures state of the art report	This is a state-of-the-art report summarising available data and information on non-destructive testing methods and technologies for application to nuclear power plant safety-related concrete structures.

Author	Reference	Title	Description
British Standards Institution	BS EN 14629:2007	Products and systems for the protection and repair of concrete structures - Test methods - Determination of chloride content in hardened concrete	This standard provides procedures for the sampling and analysis of concrete for chloride that is acid-soluble under the conditions of test.
Laboratoire Central des Ponts et Chaussées	LCPC Test method no. 66 (2004)	Reactivity of a concrete mix design with respect to delayed ettringite formation – Performance testing	This test method characterises the risk of expansive reactions with respect to delayed ettringite formation.
RILEM	prEN 12390-10 (2016)	RILEM Recommended Test Method: AAR-0 - Outline guide to the use of RILEM Methods in the assessment of the alkali-reactivity potential of aggregates	This document provides guidance on the integrated use of the assessment procedures described in AAR-1.1 & 1.2, AAR-2, AAR-3, AAR-4.1 and AAR-5 including preliminary advice on the interpretation of their findings.
British Standards Institution	BS 1881-204:1988	Testing concrete. Recommendations on the use of electromagnetic covermeters	This part of BS 1881 gives recommendations on and describes the principles of operation of electromagnetic devices that may be used for estimating the position, depth and size of reinforcement buried in concrete.
British Standards Institution	prEN 12390-10:2015	Testing hardened concrete - Part 10: Determination of the carbonation resistance of concrete at atmospheric levels of carbon dioxide	This document defines a test that may be used to measure the carbonation rate of any freshly cast concrete. It may be used to assess the impact of a change of a constituent, for example cement type, addition, or the impact of a change in mix proportions, for example w/c ratio, cement content, fines content.
British Standards Institution	BS EN 12390 11:2015	Testing hardened concrete – Part 11: Determination of the chloride resistance of concrete, unidirectional diffusion	This document provides a test method that may be applied to specimens cast or core specimens to assess the potential resistance properties of a concrete mix to the ingress of chloride, either from seawater or other sources.
British Standards Institution	prCEN/TS 12390-12	Testing hardened concrete - Part 12: Determination of the potential carbonation resistance of concrete: Accelerated carbonation method	This document defines a test method that may be applied to cast test specimens to assess the potential carbonation resistance properties of a concrete mix.
3.4. Steel reinforcement			
British Standards Institution	BS EN 10020:2000	Definition and classification of grades of steel	This standard defines the term "steel" and classifies steel grades into non-alloy, stainless steel and other alloy steels by chemical composition, and main quality classes defined by main property or application characteristics for non-alloy, stainless and other alloy steels.

Author	Reference	Title	Description
British Standards Institution	BS 8666:2005	Scheduling, dimensioning, bending and cutting of steel reinforcement for concrete - Specification	This standard covers form of schedule, form of bar or fabric label and tolerances on cutting and bending dimensions
British Standards Institution	BS 6744:2016	Stainless steel bars. Reinforcement of concrete. Requirements and test methods	This standard specifies the requirements and test methods for solid stainless steel bars used for the reinforcement of concrete. It is applicable to ribbed stainless steel bars in grade 500.
British Standards Institution	BS EN 10080:2005	Steel for the reinforcement of concrete - Weldable reinforcing steel - General	This standard gives general requirements and definitions for the performance characteristics of weldable reinforcing steel used for the reinforcement of concrete structures.
British Standards Institution	BS 4449:2005 +A3:2016	Steel for the reinforcement of concrete - weldable reinforcing steel - bar, coil and decoiled product - specification	This standard contains provisions for three steel grades, all of 500 MPa characteristic yield strength, but with different ductility characteristics. The three grades are B500A, B500B and B500C. It details steelmaking and manufacturing processes, product characteristics, evaluation of conformity and testing.
3.5. Precast concrete			
British Standards Institution	BS EN 13369:2018	Common rules for precast concrete products	This standard details the requirements, criteria and evaluation of conformity for unreinforced, reinforced and prestressed concrete products made of compact light, normal and heavy weight concrete.
3.6. Execution			
British Standards Institution	BS 5975:2008 +A1:2011	Code of practice for temporary works procedures and the permissible stress design of falsework	This standard gives practical guidelines on the design, specification, construction and the use and dismantling of falsework.
British Standards Institution	BS EN 13670:2009	Execution of concrete structures	This standard provides requirements for the execution of concrete structures and applies to in-situ work and prefabricated concrete elements, covering both permanent and temporary concrete structures.
The Concrete Society	Concrete Society Publication CS030 2012	Formwork: a guide to good practice	This guide provides good practice in the design, specification, construction and safe use of formwork for both in-situ and precast concrete.
The Concrete Society	Concrete Advice no. 37, 2016	Mould release agents	This document describes the categories of release agents currently available, outlining their advantages and disadvantages.

Author	Reference	Title	Description
4. Documents relevant to the design and manufacture of DCI containers			
International Organization for Standardization	ISO 2892:2007	Austenitic cast irons - classification	This standard specifies the grades of austenitic cast irons in terms of graphite form and matrix structure.
International Organization for Standardization	ISO 16112:2017	Compacted (Vermicular) graphite cast irons – classification	This standard specifies five grades of compacted (vermicular) graphite cast irons.
KB Sorenson, RJ Salzbrenner (Sandia National Laboratories)	(1988)	Quality Assurance aspects in using ductile cast iron for transportation casks	This paper presents a methodology to ascertain whether production DCI casks meet the specified standard of material quality.
British Standards Institution	BS EN 1564:2011	Founding. Ausferritic ductile cast irons.	This standard defines the grades and corresponding performance requirements for ausferritic ductile cast irons.
British Standards Institution	BS ISO 17804:2005	Founding – Ausferritic spheroidal graphite cast irons - classification	The standard sets out the classification system for ausferritic graphite cast iron.
British Standards Institution	BS EN 13835:2012	Founding. Austenitic cast irons.	This standard specifies the grades and corresponding requirements for austenitic cast irons. These requirements are specified in terms of: graphite form and metal structure, chemical composition and mechanical properties.
British Standards Institution	BS EN 1370:2011	Founding – examination of surface condition.	This standard provides guidance upon the specification and examination of as cast surfaces.
British Standards Institution	BS EN 1559-1:2011	Founding – Technical conditions of delivery – Part 1: General	This standard sets out a framework for the specification of castings. It is intended to be used in conjunction with complementary parts which provide more specific requirements for particular materials.
British Standards Institution	BS EN 1559-2:2014	Founding. Technical conditions of deliver – Part 2: Additional requirements for steel castings	This standard sets out the additional requirements, to be used in conjunction with BS EN 1559-1, for steel castings.
British Standards Institution	BS EN 1559-3:2011	Founding. Technical conditions of delivery – Part 3: Additional requirements for iron castings	This standard sets out the additional requirements, to be used in conjunction with BS EN 1559-1, for iron castings.
British Standards Institution	BS EN 1563:2018	Founding. Spheroidal cast iron	This standard defines the grades and the corresponding requirements for spheroidal graphite cast irons.
British Standards Institution	BS EN ISO 8062 3:2007	Geometrical product specifications (GPS) – Dimensional and geometrical tolerances for moulded parts – Part 3: General dimensional and geometrical tolerances and machining allowances for castings	This standard specifies general dimensional and geometrical tolerances, as well as machining allowance grades, for castings as delivered to the purchaser.

Author	Reference	Title	Description
British Standards Institution	BS EN ISO 9712:2012	Non-destructive testing. Qualification and certification of NDT personnel	This standard establishes principles for the qualification and certification of personnel who perform industrial non-destructive testing, as would be applied to cast components.
British Standards Institution	BS EN 1369:2012	Founding – magnetic particle inspection	This standard sets out the requirements for magnetic particle inspection including quality levels for cast components.
British Standards Institution	BS EN 12680-3:2011	Founding – ultrasonic examination – Part 3: Spheroidal graphite cast iron castings	This standard specifies the requirements for ultrasonic examination of spheroidal graphite cast irons.
International Organization for Standardization	BS ISO 1083:2018	Spheroidal graphite cast irons - classification	This standard defines the grades and the corresponding requirements for spheroidal graphite cast irons.
ASTM International	ASTM A874/A874M (98) 2014	Standard specification for ferritic ductile iron castings suitable for low-temperature service	This specification covers ductile iron castings suitable for service at temperatures of –40°C and above.
British Standards Institution	BS EN ISO 4618:2014	Paints and varnishes - Terms and definitions	This standard defines the terms used in the field of coating materials.
British Standards Institution	BS 7079:2009	General introduction to standards for preparation of steel substrates before application of paint related products.	This standard gives a general introduction to all the British standards for steel surface preparation. It gives general information on all the separate groups of standards, along with a complete listing of all the published standards that cover abrasive blast cleaning, hand and power tool cleaning and flame cleaning of steel substrates.



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