Radioactive Waste Management

WPSGD no. WPS/502/01

Geological Disposal

Guidance on the production of encapsulated wasteforms

August 2015

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WASTE PACKAGE SPECIFICATION AND GUIDANCE DOCUMENTATION
GUIDANCE ON THE PRODUCTION OF ENCAPSULATED WASTEFORMS

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

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

This document provides guidance on the achievement of the requirements specified in *Wasteform specification for waste packages containing low heat generating waste* (WPS/501) as they apply to wasteforms in which waste has been conditioned in a manner that involvesthe use of an encapsulating medium. It provides an explanation of the rationale behind the definition of the requirements specified by WPS/501, together with information to assist waste packagers in the development of approaches for the packaging of waste in a manner that will allow those requirements to be achieved.

The WPSGD is subject to periodic enhancement and revision. Users are therefore advised to refer to the RWM website to confirm that they are in possession of the latest version of any documentation used.

WPSGD DOCUMENT NUMBER WPS/502- VERSION HISTORY		
VERSION	**DATE**	**COMMENTS**
WPS/502/01	August 2015	Aligns with Generic Specification for waste packages containing low heat generating waste (NDA/RWM/068) as published August 2012. Produced, along with WPS/503 (Guidance on non-encapsulated wasteforms), to support WPS/501 (Wasteform Specification for waste packages containing low heat generating waste). Replaces WPS/800, WPS/810 and WPS/820.

List of Contents

Abbreviations and acronyms used in this document

ALARP	as low as reasonably practicable
BAT	best available techniques
DSSC	Disposal System Safety Case
DSTS	Disposal System Technical Specification
EBS	engineered barrier system
ESC	Environmental Safety Case
FE	finite element
GDF	geological disposal facility
GGBS	ground granulated blast furnace slag
GWPS	Generic Waste Package Specification
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
ILW	intermediate level waste
LHGW	low heat generating waste
LLW	low level waste
MNOP	maximum normal operating pressure
NAPL	non aqueous phase liquid
NDA	Nuclear Decommissioning Authority
PC	Portland cement
PFA	pulverised fly ash
RWM	Radioactive Waste Management Ltd
VES	vinyl ester styrene
WAC	waste acceptance criteria
WPS	Waste Package Specification
WPrS	Waste Product Specification
WPSGD	Waste Package Specification and Guidance Documentation

1 Introduction

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

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

The packaging specifications form a hierarchy which comprises three levels:

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

The WPS, together with a wide range of explanatory material and guidance that users will find helpful in the development of proposals to package waste, make up a suite of documentation known as the *Waste Package Specification and Guidance Documentation* (WPSGD). For further information on the extent and the role of the WPSGD, all of which can be accessed via the RWM website, reference should be made to the *Introduction to the RWM Waste Package Specification and Guidance Documentation* [3].

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

For waste packages containing low heat generating waste[1] (LHGW), RWM has produced the *Generic Specification for waste packages containing low heat generating waste* [5]. This specification defines high level requirements for the properties of the wasteforms which are contained in such waste packages and these are further developed in the *Wasteform Specification for waste packages containing low heat generating waste* [6].

The wasteforms that can be used for the packaging of LHGW are of two basic types:

- Encapsulated wasteforms where the waste has been rendered into an effectively monolithic form by intimately mixing with an encapsulating medium; or
- Non-encapsulated wasteforms where the waste may have undergone some pre-treatment (e.g. size reduction and/or drying) and is loaded into a waste container without further conditioning.

1 This broad category of waste includes intermediate level waste (ILW) and other wastes with similar radiological properties which can be disposed of in accordance with the same geological disposal concepts as those defined for ILW.

This document provides guidance on the production of wasteforms with the required propertiesas they apply to the former approach. A counterpart dealing with the achievement of these requirements for non-encapsulated wasteforms is also available [7]. These two documents support, and should be read in conjunction with, the WPS for waste packages containing LHGW, and their supporting guidance [8, 9].

This document is structured in the following manner:

- Section 2 provides background information on the manner in which the requirements for waste packages are defined from the role that they play in the geological disposal system.
- Section 3 discusses the issues which can arise from the encapsulation of wastes, identifies the types of waste that may be suitable for packaging in such a manner, and the approaches that can be adopted.
- Section 4 identifies the generic requirements for wasteforms, as specified in the Wasteform Specification (i.e. [6]) and discusses their application to encapsulated wasteforms.
- Section 5 explains the reasons for the definition of the generic wasteform requirements and provides guidance on how they can be achieved by encapsulated wasteforms.
- Section 6 provides guidance on the development of processes for the encapsulation of waste.
- Section 7 discusses the benefits and limitations of a number of encapsulants that have been used in the conditioning of LHGW.
- Section 8 provides guidance on how a waste packager can demonstrate that the requirements of the Wasteform Specification, together with those of the relevant packaging specification, will be achieved by an encapsulated wasteform.
- A glossary of important terms and phrases is appended to this document.

2 Background

2.1 The definition and purpose of packaging specifications

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

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

RWM has established the *Disposability Assessment process* [10] to support those responsible for the packaging of higher activity wastes by demonstrating that the waste packages they propose to produce will be passively safe and disposable, and in line with regulatory expectations for the long term management of the waste they contain [11]. In this manner RWM also demonstrates that waste packages will be capable of providing the barrier to the release of radionuclides and other hazardous materials that is required of them as part of a multiple barrier geological disposal system. A *Letter of Compliance* (LoC) is issued for each specific design of waste package which has been shown to be disposable by way of the Disposability Assessment process.

The Disposability Assessment processalso plays an important role in underpinning the generic Disposal System Safety Case (DSSC) [12] by demonstrating that the geological disposal concepts considered therein will be appropriate for the actual wastes they will be expected to cover. The process also serves to identify wastes that could challenge the disposal concepts currently assumed for particular categories of waste and thereby allow early consideration of what changes may be required to these concepts to permit such wastes to be accommodated. RWM has produced guidance on the manner by which waste packagers should prepare submissions for the disposability assessment of their proposals to package waste [13].

With waste packages being manufactured at many sites throughout the UK, and by a number of different organisations, the needs of ensuring cost-effectiveness, safety and environmental protection in the long-term are promoted by the adoption of common approaches to waste packaging. In support of these needs, RWM has defined a range of waste containers with standardised features (e.g. dimensions, handling/stacking arrangements) which can be used to produce waste packages, these containers being identified in the DSTS [4]. The definition of waste containers in this way will help to ensure a high level of confidence that all waste packages manufactured according to the requirements set out in the WPSGD will be compatible with future transport and GDF infrastructure and facilities.

RWM considers that the existing standardised waste containers will be suitable for use in the packaging of the majority of the ILW[2] predicted to arise in the UK. However, it is

[2] These containers may also be suitable for use in the packaging of a wider range of LHGW, as discussed in the Generic Specification [5].

acknowledged that these waste container designs may not suit all of the needs of individual waste producers, and that additional designs may be required for the packaging of particular wastes.

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

2.2 The role of the waste package in geological disposal

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

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

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

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

In the generic DSTS [4] the concept of *safety functions* is developed as a means of defining the roles played by each of the barriers in the post-closure performance of a GDF. This concept is further developed in the DSSC in which the safety functions that are required of waste packages during transport and the GDF operational period are also considered [14]. The GWPS identifies the safety functions specific to waste packages which will be required during transport and the period up to the time when a GDF is backfilled, and during the GDF post-closure period. The safety functions required in these periods can be summarised as:

- During transport and the GDF operational period:
    - Provide containment of radionuclides and other hazardous materials during normal operations and under accident conditions;
    - Limit radiation dose[3] to workers and members of the public;

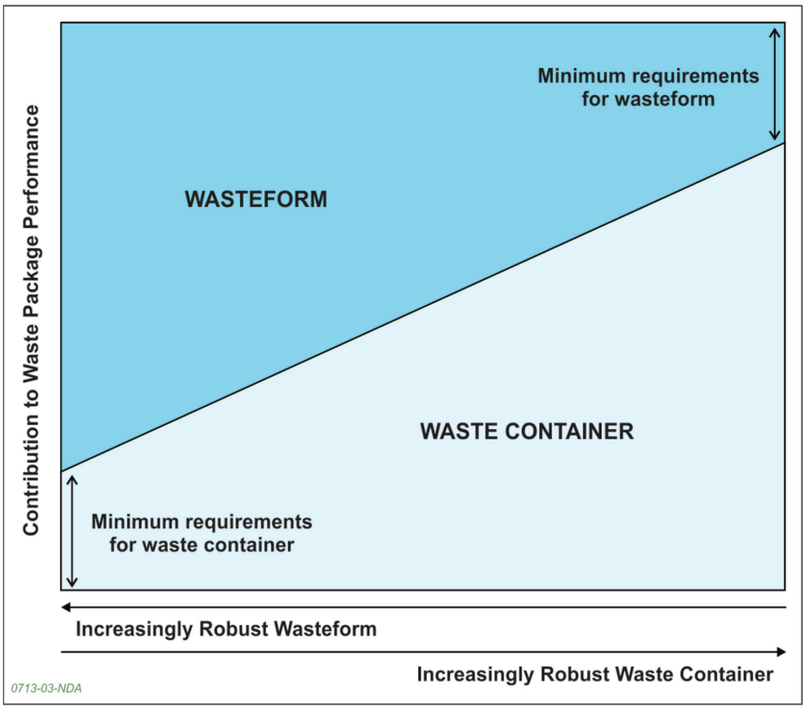
[3] In this context radiation dose is that which could result from exposure to direct radiation from the surface of the waste package.

- Preclude criticality;
- Provide the means of safe handling; and
- Withstand internal and external loads.

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

Both the waste container and the wasteform can contribute to the achievement of the required performance of a waste package, the relative importance of each generally depending on the robustness of the former. This is illustrated in Figure 1 which shows in stylised form how the use of a more robust waste container can reduce the required contribution of the wasteform to overall waste package performance. Figure 1 also shows that for all waste packages both the waste container and the wasteform will be required to play some role. It should also be noted that it is the overall performance of the waste package, rather than that of its two components, that is the governing factor in judging its disposability.

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



2.3 The definition of waste package types

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

- For use with LHGW with low specific activity, such as would not generally require the extensive use of remote handling techniques, waste containers, typically made from thin section stainless steel and/or concrete, and incorporating integral radiation shielding[4] can be used to create *shielded waste packages.* Such waste packages would generally be expected to be capable of being transported through the public domain without additional protection and would therefore qualify as transport packages in their own right.

- For use with LHGW with higher specific activity, such as would generally require the use of remote handling techniques, waste containers typically made from thin-section stainless steel,can be used to create*unshielded waste packages.* Because of their high external radiation dose rate, or requirements for the containment of their contents, such waste packages would be expected to be transported through the public domain ina protective transport container.
- For all types of LHGW, thick-walled (i.e. many 10's of mm) containers, typically made from ductile cast iron, can be used to provide both radiation shielding and physical containment of their contents, and to create *robust shielded waste packages.* Such waste packages are capable of being stored, transported and disposed of without the need for remote handling techniques or for additional shielding or containment.

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

3 The use of encapsulated wasteforms in the packaging of LHGW

3.1 The definition of an encapsulated wasteform

The Glossary at the end of this Guidance defines a wasteform as:

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

The Wasteform Specification for LHGW requires that [6]:

> *'The wasteform shall be designed to immobilise radionuclides and other hazardous materials so as to make an appropriate contribution to waste package performance during all stages of long-term management. For some wastes (e.g. sludges and those containing significant particulate material) such immobilisation will require the use of an encapsulating matrix whilst for others (e.g. irradiated metals) immobilisation may be provided by the nature of the waste itself.'*

At this point it is important to draw a distinction between 'immobilisation' and 'encapsulation' as these terms refer to the radionuclides and other hazardous materials that are associated with a waste. Immobilisation is by definition a process that eliminates, or at least reduces, the mobility of radionuclides whereas encapsulation is a possible means of achieving immobilisation. The means by which adequate immobilisation is achieved in an encapsulated wasteform will, however, depend to a great extent on the physico-chemical properties of the waste, and the chemical properties of the radionuclides in question.

The word 'encapsulate' means *'to enclose in or as in a capsule',* a description which partly captures its meaning when applied to the conditioning of waste for geological disposal. Historically the preference in the UK has been for wasteforms to be encapsulated, in which a waste is intimately mixed with a medium such as a cementitious grout to form an effectively monolithic wasteform. Such an approach has been shown to be capable of producing wasteforms which satisfy all of the requirements for safe geological disposal, for wastes with a wide range of physico-chemical properties. However encapsulation may be effected by enclosing the waste within an annular grouted wasteform, in which the grout does not infiltrate the waste, or by other treatment processes, such as the drying and/or compaction of sludge wastes. By contrast a 'non-encapsulated' wasteform is one where the waste has only received more basic treatment (e.g. size reduction) before being placed into a waste container, and receives little or no subsequent conditioning. The nature and means of production of a range of encapsulated wasteforms are discussed further in Section 3.4.

3.2 Waste types potentially suitable for encapsulation

In order for a waste to be deemed suitable for a conditioning process that would result in the creation of an encapsulated wasteform there are a number of basic criteria that will have to be satisfied [15]. At the highest level a waste package containing an encapsulated wasteform must be capable of satisfying the necessary requirements of the Generic Specification [5]. This will include providing the required degree of containment of the radionuclides and other hazardous materials associated with the waste during interim storage, transport and the operational and post-closure periods of a GDF.

Intimate encapsulation using cementitious of polymeric materials has been shown to be capable of providing wasteforms with suitable properties for a wide range of waste types, it is therefore more useful to consider which wastes for which encapsulation may not offer the optimal approach, and for which non-encapsulation may be preferred.

Wastes which are difficult to infiltrate may not be suitable for encapsulation, or may require extensive pre-treatment which could result in excessive radiation dose to workers. The physical structure of wastes such as filters are inherently complicated and may need dismantling before conditioning for disposal [16]. Wastes such as plutonium contaminated material, which comprises a mixture of widely varied materials contaminated with plutonium and uranium in fine particulate form, present a similar challenge and the solution has been to super-compact the waste in 'sacrificial' 200 litre mild steel storage drums and to 'entomb' the compacted wastes within an annular grouted wasteform. Such an approach would not be considered to be one which resulted in an 'encapsulated wasteform' [7].

Some wastes, such as those that arise from the decommissioning of nuclear reactors, contain radionuclides which are the result of neutron irradiation, and exist within the atomic structure of the waste such that they are effectively immobile. There may be no benefit in encapsulating such wastes, indeed such an approach could have a deleterious effect if chemical reactions were to take place between the encapsulant and the waste and result in the release of previously immobile radionuclides. This could also be the case for metal wastes into which tritium and other radioactive gases have diffused.

For many wastes, the use of a robust shielded waste container (see Section 2.3) can remove the need for encapsulation. Waste packages manufactured using such a waste container would lie towards the right hand side of Figure 1, where the properties of the wasteform make little contribution to the performance of the waste package and, as a consequence, the waste it contains may need only basic conditioning.

In summary, there are a number of waste types for which non-encapsulation, especially if combined with the use of a robust shielded waste container, could offer a more optimum approach to their packaging. These include solid wastes which are dry, chemically inert and relatively free of fine particulate material. For guidance on the development of a packaging process involving non-encapsulation reference should be made to the counterpart to this guidance [7].

3.3 Selection of the waste container for use with an encapsulated wasteform

In principle, any of the three waste container types identified in Section 2.3 would be suitable for use with an encapsulated wasteform. Indeed some of the standardised designs, notably the 3 cubic metre drum, have been developed specifically for use with liquid and slurry type wastes for which in-container mixing with an encapsulating medium is used to create a wasteform with the necessary properties.

The suitability of a specific design of waste container for use with an encapsulated wasteform will depend to a large degree on the physico-chemical nature of the waste. In Section 2.2the relative contributions of the waste container and the wasteform to the achievement of the required performance of the waste package is discussed. In general an encapsulated wasteform will make a significant contribution to waste package performance and this will mean that, beyond its basic functions (i.e. to provide basic containment and protection of its contents as well as a means of handling the waste package etc.), the role played by the container will be less than, for example, that provided by a robust shielded waste container.

Ultimately it is the combined performance of a specific combination of waste container and wasteform that will govern the disposability of a proposed waste package, this being judged by way of the Disposability Assessment process. In this context the following questions will need to be particularly addressed by a packaging proposal:

- Does the waste possess properties that could accelerate corrosion of the internal surface of the waste container and threaten its ability to achieve the required durability of integrity and/or alter the waste package performance?
- Is the waste container capable of providing adequate radiation shielding?

- Is the waste container capable of dealing with the gas generated by the wasteform?
- Are the properties of the wasteform such that adequately low waste package impact and fire accident release fractions[5] can be achieved?

3.4 Types of encapsulated wasteforms

A range of wastes have been packaged for geological disposal using conditioning processes that involve encapsulation. ‘Intimate encapsulation’ has been achieved or proposed using three basic approaches; grout infilling of heterogeneous solid wastes, in-container mixing of fluid wastes with grout, and external mixing of waste and grout followed by pouring the mixture into the waste container. Encapsulation has also been achieved by surrounding waste, which may have been compacted, with an annulus of grout to form an ‘annular grouted’ wasteform.

Work is currently underway to investigate the feasibility of using high temperature processes to produce monolithic ‘vitrified’ wasteforms for some types of ILW. This approach is beyond the scope of this guidance but may be the subject of future guidance, if any of the processes currently under development proves to be effective in producing wasteforms with the necessary properties.

a) Grout infilling of heterogeneous solid waste

This approach has been extensively used for the conditioning of solid wastes, notably operational wastes arising from the fuel reprocessing plants at Sellafield. The waste is placed within the waste container and in-filled with a fluid grout, either cementitious or polymeric. Depending on the shape and nature of the solid waste, the process may include vibration or pressure grouting to improve infiltration and assist in the elimination of voids. The design of the waste containers (i.e. 500 litre drums and 3 cubic metre boxes) that have been used to date, have incorporated features such as grout introduction tubes, dewatering tubes and/or an anti-flotation plate (to prevent less dense items of wastes from floating to the surface of the grout).

b) In-container mixing of fluid wastes

This approach has been used for the conditioning of liquid, sludge and slurry wastes at Sellafield, Dounreay and Trawsfynnydd. A key feature of the waste container design is the incorporation of a device such as a paddle for mixing the waste and the encapsulating medium to form a relatively homogeneous wasteform. After mixing, the paddle is disconnected from the drive mechanism and remains in the wasteform, which is then allowed to set. The 500 litre drum (Figure 3) and 3 cubic metre drum waste containers have been used in this manner for a variety of wastes with wide ranging physico-chemical properties.

5 Release fraction is defined as the fraction of the total contents of a waste package (in terms of the mass of material or the activity associated with that material) released as a consequence of a defined accident.

Figure 2 500 litre drum for heterogeneous solid waste

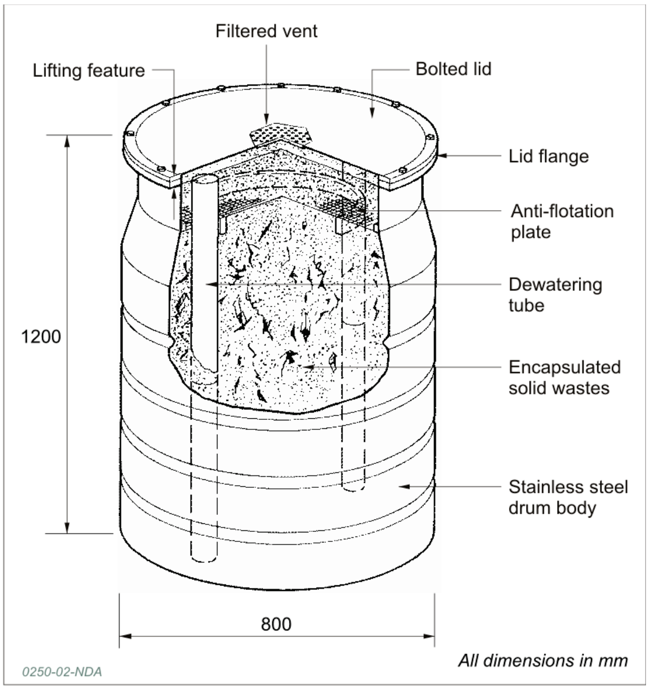
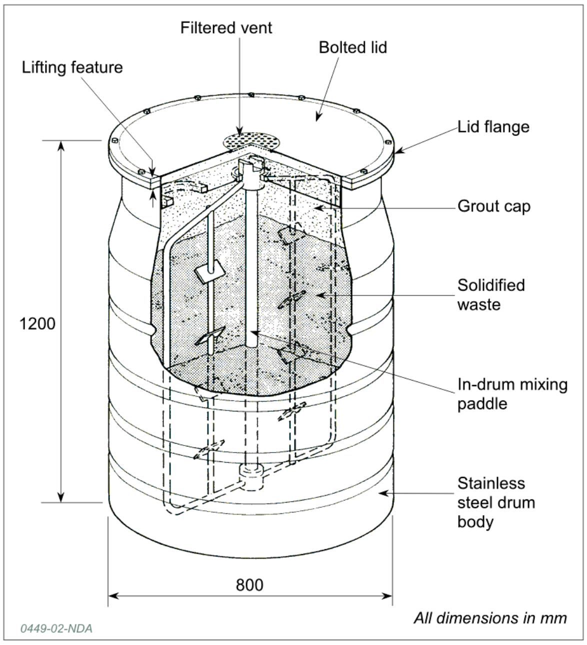


Figure 3 500 litre drum with in-drum mixing furniture



c) External mixing of waste and grout

For some wastes the option to mix the waste and encapsulating medium outside of the final waste container has advantages. This is particular applicable to legacy wastes which can comprise a mixture of materials with a wide range of physico-chemical properties and for which a larger waste container (e.g. the 3 cubic metre box) is more suitable. Such wastes can be 'tumble mixed' with a cementitious grout and the contents of the mixing vessel tipped into the waste container. As well as ensuring good mixing of the waste and grout the mixing process can also be sufficiently vigorous to promote such beneficial effects as breaking up of the waste (to aid homogeneity) and the puncturing of sealed vessels within the waste (to reduce the possibility of sealed voids).

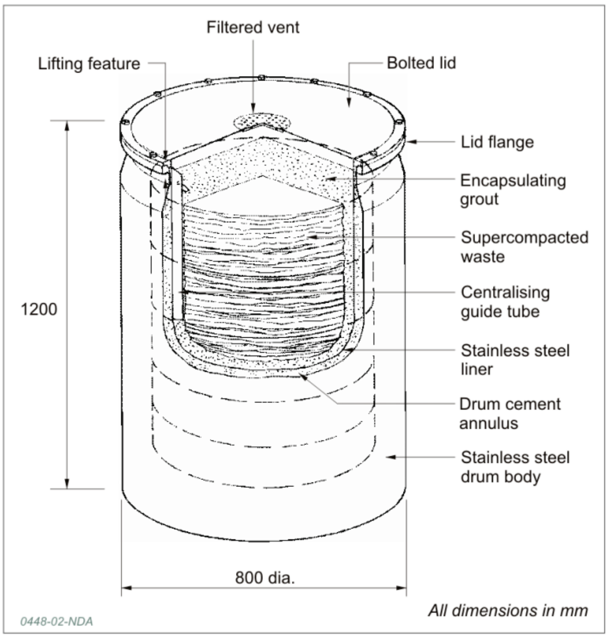
d) Use of a grout annulus

Solid waste can be enclosed within a wasteform by the use of a surrounding layer of cementitious or polymeric grout. In such cases the grout is not primarily intended to penetrate and intimately encapsulate the waste, but rather to provide additional containment (i.e. over and above that provided by the waste container). As well as providing such containment an annular grouted wasteform can also provide radiation shielding and physical and thermal protection of the waste under accident conditions.

The 500 litre drum has been used with annular grouted wasteforms for the packaging of 'soft' wastes such as plutonium contaminated material (Figure 4). In such cases waste held in a sacrificial container (a 200 litre mild steel drum) is super-compacted to form 'pucks' which are placed within the 500 litre drum, and surrounded by a grout annulus, which could be pre-cast (i.e. as part of the waste container) or cast following placement of the pucks in the centre of the waste container using suitable furniture.

Super-compaction is not a pre-requisite for the use of an annular grouted wasteform, in that waste could be placed within a basket (which could be perforated to permit some penetration by the grout) and surrounded with grout, either pre-cast or poured into the container after placement of the basket.

Figure 4 500 litre drum with annular grouted wasteform



3.5 The selection of a process for the encapsulation of a waste

The selection of the waste container type and waste conditioning materials and processes for the packaging of a specific type of waste will depend on a variety of factors. These include the physico-chemical properties of the waste, the range of those properties within the waste stream, and the total volume of the waste stream. Also the availability of the facilities and/or plans for the manufacture and interim storage of the final waste packages, and their nature (e.g. the degree of shielding that such a facility would provide). The selection process should also include optioneering to consider environmental aspects and the cost of the whole process of the long term management of the waste including retrieval, packaging, interim storage, transport and disposal.

It is a UK regulatory requirement that a waste packager shall identify and select the optimum approach to the packaging of a specific waste stream, using a best available technique (BAT) study process. Each waste packaging proposal submitted for disposability assessment should therefore be underpinned by a BAT study. Further information and guidance on the selection of packaging processes for ILW waste streams is provided by [17, 18]. To aid in this selection process it is recommended that a waste packager engages with RWM at an early stage in the selection of an optimum waste packaging process for a specific waste stream (or waste streams). RWM can then provide the most up to date input information and advice on the disposability of the range of waste packaging options being considered.

RWM has produced thematic guidance on the packaging of a number of specific types of ILW, including radon generating wastes [19], filters [16], closed sources [20] and tritium bearing wastes [21]. Whilst targeted at these specific waste types this guidance can also be used as input to BAT studies during the development of packaging plans for other waste types.

In the event that a decision is made to encapsulate a specific waste stream, the choice of the material used for that purpose will clearly be a fundamental part in the development of the packaging process. This is likely to control several key aspects of the process and of the design of the packaging plant. These include:

- the type of waste container to be used and the number of waste packages anticipated to be produced (based on the acceptable waste loading);
- the overall cost of packaging the waste stream;
- the anticipated plant throughput (based on wasteform parameters such as mixing and cure time); and
- the footprint of the packaging plant, including storage requirements for raw materials, weighing and blending equipment etc.

Most importantly, the selected encapsulant will control the performance of the wasteform[6]; particularly in terms of the expected evolution of the wasteform and the consequences of such evolution for the long-term performance of the waste package. The selection of an appropriate encapsulant for a specific waste stream should result in the following:

- a wasteform with acceptable performance for the full range of materials present in the waste stream;
- the operation of a practicable and efficient packaging plant;
- an overall cost-effective waste packaging solution; and
- acceptable security of supply of the encapsulant materials [22].

It is good practice that the selection of the preferred encapsulant should be included as part of the BAT studies used to guide selection of the optimum waste packaging process [11].

Further guidance on the selection of an encapsulant is given in Section 6.

[6] Wasteform performance is judged as its ability to be compliant with the relevant WPS, the Wasteform Specification [6] and from the outcomes of the safety evaluations carried out as part of a disposability assessment.

4 Generic requirements for encapsulated wasteforms

This Section provides guidance on the requirements defined by the Wasteform Specification for waste packages containing LHGW[6] as they are applied to encapsulated wasteforms.

The GWPS [2] provides the highest level definition of the requirements for wasteforms by stating that:

> *'The properties of the wasteform shall be such that, in conjunction with those of the waste container, it satisfies all of the requirements for the waste package.*
>
> *The properties of the wasteform shall comply with the requirements for containment within the geological disposal concept, as defined by the GDF safety case.'*

For waste packages containing LHGW the Generic Specification [5] adds:

> *'The physical, chemical, biological and radiological properties of the wasteform shall:*
>
> - *make an adequate contribution to the overall performance of the waste package; and*
> - *have no significant deleterious effect on the performance of the waste container.*
>
> *Evolution of the wasteform shall ensure maintenance of the waste package properties that are necessary for safe transport to and operations at a GDF.*
>
> *Evolution of the wasteform shall ensure maintenance of the required safety functions for post-closure performance as set out in the Environmental Safety Case (ESC).'*

This final requirement is quantified in each of the WPS for the specific designs of waste package containing LHGW (e.g. [23]) as:

> *'The evolution of the wasteform shall ensure maintenance of the waste package properties, for a period of 150 years following manufacture of the waste package.'*

To aid in the application of these requirements to 'real' packaging situations the Wasteform Specification has been produced to define requirements for the key properties that are known to affect wasteform quality and performance.

The Generic Specification assumes that the properties of the wasteform will play a key part in ensuring the passive safety of a waste package and this is largely achieved by ensuring that the waste to be packaged possesses the properties discussed in Section 3.2 and that a suitable conditioning process is selected, as discussed in Section 3.4. It also lists *target* criteria for the wasteform content and properties that should be controlled, in order that it will be compliant with this requirement. Typically this includes controls on the presence of the following types of material and/or wasteform properties that could affect the performance of a waste package:

- free liquids;
- activity or hazardous materials in fine particulate form;
- voidage;
- in-homogeneity;

- reactive materials;
- other hazardous materials; and
- materials that could have a deleterious effect on the other barriers that make up the geological disposal system.

The extent to which such controls will be required for any wasteform will be very dependent on the robustness of the waste container, as well as the consequences of the presence of materials with such properties on the performance of the proposed specific design of waste package. The significance of their presence is assessed as part of the disposability assessment of a packaging proposal, along with the following additional key performance issues:

- The potential for chemical reactions between the wasteform (i.e. the waste and the encapsulant) and the inner surfaces of the waste container, or expansive behaviour of the waste that could result in excessive forces being exerted on the waste container walls and result in a loss of some aspect of waste package performance.
- Evolution of the wasteform, resulting from chemical, biological and radiation induced processes, may change its properties with time. It is important that such evolution will not result in effects that make the waste package incompatible with the needs of transport or the requirements for safety during the GDF operational period. This notably includes the generation of gas by the wasteform and the loss of passive safety.
- In the GDF post-closure period the wasteform may continue to play a role in overall safety. Accordingly the consequences of waste evolution should be such that the relevant assumptions that underpin the post-closure safety case are satisfied and that the wasteform will continue to make an appropriate contribution to the overall performance of the waste package and the geological disposal system as a whole. For example, the degradation of organic materials present in some wasteforms (e.g. cellulose waste materials) is known to produce gases as well as chemical species that can act as complexants. Complexants can increase the solubility of some radionuclides including plutonium, and reduce the sorption capacity of the engineered and geological barriers. Therefore controls on the quantities of complexant generating materials in a wasteform may be required [24].

The Generic Specification [5] and the DSSC [12] also state that the wasteform, as part of the complete waste package, may be required to provide a key safety function in the post-closure period. This requires the wasteform to provide a stable, low solubility matrix that limits the release of the majority of radionuclides by dissolving slowly in the groundwater that come into contact with it. As the DSTS explains, the required safety functions of the engineered barriers in the GDF, including the wasteform, will depend on the characteristics of the waste and the geological environment. Such requirements will therefore not be explicitly defined and applied to waste packages until a site for the GDF is known. To date, safety assessments of the groundwater pathway from the GDF have assumed that the release of radionuclides from waste packages into the backfill is instantaneous (i.e. no credit is taken for any ability of the wasteform to restrict radionuclide leaching). Thus there are no specified limits on the leaching performance of wasteforms.

5 Guidance on the production of encapsulated wasteforms

The key wasteform parameters that could affect the quality and performance of the wasteform are defined by the Wasteform Specification [6] where they are grouped under six categories:

- Physical immobilisation;
- Mechanical and physical properties;
- Chemical containment;
- Hazardous materials;
- Gas generation; and
- Wasteform evolution.

It is best practice to design, demonstrate and manufacture a wasteform that meets all the requirements specified by the Wasteform Specification. It is however recognised that some of these requirements are inter-related and in specific circumstances an optimum waste packaging process may require the relaxation of one or more wasteform requirements to facilitate the production of a waste package which possesses acceptable overall performance. The need for and acceptability of a relaxation of any of wasteform performance requirements is determined as part of the disposability assessment of the packaging proposal to which it applies. Guidance on this matter is best obtained on a case by case basis through early engagement with RWM in advance of a formal submission for the disposability assessment of a packaging proposal.

The consequences of waste encapsulation for the criticality safety of waste packages is also considered below, despite this not being explicitly addressed in the Wasteform Specification.

The structure of the following sub-sections is, for each of the categories listed above, to:

- State the requirement defined by the Wasteform Specification;
- Provide a basic explanation of the wasteform property;
- Explain why the requirement is necessary;
- Provide guidance on how the requirement can be achieved; and
- Explain how that achievement can be demonstrated.

It should be noted that, where the words *shall* and *should* are used in criteria within the Wasteform Specification, and in the packaging specifications, their use is consistent with the recommendations of BS 7373:1998 [25] and that they have the following meaning:

- *shall* denotes a criterion which is derived from consideration of a regulatory requirement and/or which forms the basis for package standardisation;
- *should* denotes a criterion which is considered as a target, and for which variations may be possible following discussion with RWM.

A number of the requirements discussed below include quantified ‘screening levels’. These values are defined to provide guidance to waste package designers by indicating the levels below which no specific justification of wasteform performance would be required as part of a submission for the disposability assessment of a packaging proposal. It should be noted that these screening levels are not intended to be used as a sole basis for the development of packaging proposals as, in many cases, the actual limiting values for specific designs of wasteform and/or waste package may be significantly higher.

5.1 Physical immobilisation

The requirement:

The wasteform shall be designed to immobilise radionuclides and other hazardous materials so as to make an appropriate contribution to waste package performance during all stages of long-term management. For some wastes (e.g. sludges and those containing significant particulate material) such immobilisation will require the use of an encapsulating matrix whilst for others (e.g. irradiated metals) immobilisation may be provided by the nature of the waste itself.

The adequate immobilisation of radionuclides by a wasteform is required to ensure that the release of activity from a waste package during normal and accident conditions does not result in workers (either at the site of arising, during transport or at the GDF) or the public receiving radiation doses that exceed permissible limits.

What is immobilisation?(see also Section3.1)

To ensure that the performance of a waste package is acceptable during all stages in its long-term management, adequate immobilisation of radionuclides and other hazardous materials associated with the waste must be achieved by the wasteform. Immobilisation can be deemed to be 'adequate' if the release of radionuclides from a waste package under normal and accident conditions during interim storage, transport and the GDF operational period does not result in radiation doses that exceed the limits specified by the safety cases for each of those periods.

A wasteform with adequate immobilisation will typically have the following properties:

- Low and predictable releases of radionuclides and other hazardous materials following an accident (e.g. impact and/or fire);
- The consequences of wasteform evolution, in terms of the loss of immobilisation, for waste package performance will be predictable;
- Predictable release of gases at a rate consistent with the limits defined by the packaging specifications;
- Reduced solubility of key radionuclides and toxic chemicals; and
- Compatibility of wasteform properties (e.g. voidage and chemistry) with the backfilled GDF disposal vault environment.

The immobilisation of free liquids and fine particulate material less than 100 microns is considered to be a principal requirement of the wasteform (see Sections 5.1.2 and 5.1.4 for further details). In this context, immobilisation can be defined as the adequate elimination of fluidity, dispersal and freedom of movement for radionuclides and bulk material within a solid wasteform.

How is immobilisation achieved?

The immobilisation of radionuclides in an encapsulated wasteform will rely on the nature of the waste and the manner in which encapsulation has been achieved. The following sub-sections discuss the various aspects of immobilisation by encapsulated wasteforms.

5.1.1 Immobilisation of radionuclides and particulates

The requirement:

All reasonable measures shall be taken to ensure that radionuclides and other hazardous materials in the waste are immobilised and that loose particulate material is minimised.

How is the requirement achieved?

Wastes that require encapsulation to achieve adequate immobilisation are generally those that have radionuclides in particulate, liquid and/or gaseous form associated with them, or are those which contain radionuclides in volatile or soluble compounds. These waste characteristics and properties are associated with saturated solids, suspensions, sludges, dry powders, friable solid materials and solid materials that may corrode to produce activity in particulate form.

The use of a suitable encapsulant to form a solid wasteform should result in mobile radionuclides being chemically bound or physically trapped within the matrix. Similarly, the encapsulant will physically bind or envelop particulates. The result is intended to be a monolithic wasteform that is designed to control and minimise the release of radionuclides and other harmful waste components.

The required immobilisation performance of a wasteform may also be achieved by the use of design features such as a protective clean grout annulus surrounding an active wasteform (see Sections 5.1.2 and 5.1.3).

The longevity of adequate radionuclide immobilisation must also be proven, because the evolution of a wasteform over the specified 150 year period may result in physical and/or chemical degradation that could reduce the effectiveness of the immobilisation (see Section 5.6).

Basic guidance on the methods of producing an encapsulated wasteform is provided in Section 3.5. More detailed guidance on the need for and means of achieving adequate immobilisation in wasteforms can be found in [26].

How is adequate immobilisation demonstrated?

The demonstration that a wasteform can provide the required degree of immobilisation will be found in the supporting documentation that forms part of the Waste Product Specification and other evidence submitted by a waste packager as part of a submission for the disposability assessment of a packaging proposal [13]. This will notably include the R&D work which justifies the suitability of the proposed waste conditioning process selected for the specific type of waste to be packaged.

The evidence required to demonstrate adequate immobilisation by a wasteform includes the following:

- Small and large scale testing of the wasteform (see Section 8);
- Testing or modelling of the waste package to determine radionuclide releases under normal and accident conditions (see Sections 5.1.2 and 5.1.3); and
- Data to show that evolution of a wasteform over the specified 150 year period will not result in degradation that could reduce the effectiveness of the immobilisation (see Section 5.6 for details).

The evidence for adequate immobilisation provided by a wasteform design should be submitted in a staged approach as required by the Disposability Assessment process (see Section 6).

5.1.2 Response to an impact accident

The requirement:

All reasonable measures shall be taken to ensure that, in the event of an impact accident, the quantity of potentially mobile radionuclides present within the waste package, including those generated as a result of the impact accident, is commensurate with the waste package meeting the impact accident performance requirements defined by the relevant WPS.

What is an impact accident?

The transport of waste packages to a GDF, and their subsequent handling (notably their stacking in the disposal vaults) exposes them to the risk of impact accidents, including those resulting from them being dropped from significant heights on to solid floors or aggressive features, such as other waste packages. Impact accidents are a potential mechanism for the release of radionuclides from waste packages into the environment where they can result in radiation dose to workers and members of the public. The severity of impact accidents will vary depending on the type of waste package, transport package and the design of the GDF (notably the host geology).

The IAEA *Regulations for the Safe Transport of Radioactive Material*[7] [27] specify a series of mechanical tests which define the requirements for the impact accident performance of Type B transport packages[8]. This includes exposing the transport package to a drop from a height of 9m on to a flat horizontal surface and from 1m on to an aggressive feature. The release of activity from the transport package in the week following such a challenge, together with a specified thermal challenge (see Section 5.1.3), should not exceed $1A_2$. No impact accident performance is required of Type IP transport packages[9] beyond a requirement to withstand 'normal conditions of transport', which include a free drop from a height of 0.3m[10], without 'loss or dispersal of the radioactive contents[11]'.

The dose consequences of impact accidents during the GDF operational period are the subject of the HSE *Safety Assessment Principles* (SAPs) which define Basic Safety Limits (BSL) for the dose consequences of the release of activity from waste packages following accidents which include those involving impacts to waste packages [28]. The generic Operational Safety Case (OSC) uses the BSLs as targets for the dose consequences of the release of activity from waste packages following design basis accidents [29].

During the development of the DSSC, and notably of the generic GDF designs for the three host rock scenarios, a maximum vault height of 16m is envisaged [30]. This results in maximum stack heights of 11m for unshielded waste packages and 8.7m for shielded and robust shielded waste packages. A review of the potential for impact accidents affecting waste packages during the operational period of the GDF has concluded that the most severe impacts would be [31, 32]:

- For unshielded waste packages; a drop onto a flat unyielding target from a height of 11m, and onto an aggressive feature[12] from a height of 10m.
- For shielded waste packages; a drop of 10m on to an unyielding surface or aggressive feature.
- For robust shielded waste packages, assumed to be stacked up to five high; a drop onto a flat unyielding target from a height of 10.5m; and onto an aggressive feature from a height of 9m.

A more detailed discussion of the required impact accident performance of waste packages, and how this informs the evaluation of the safety oftransport and GDF operations can be found in the guidance that supports the WPS [8, 9].

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7 Referred to hereafter as the 'IAEA Transport Regulations'.

8 Unshielded waste packages are transported in shielded transport containers as Type B transport packages. The transport container will provide significant containment in the event of a release of radionuclides from the waste package.

9 Shielded waste packages are generally transported without additional protection as Type IP transport packages.

10 This height is specified for transport packages of gross masses of greater than 15t. Greater heights (of up to 1.2m) are specified for transport packages with smaller gross masses.

11 The IAEA Transport Regulations do not quantify this requirement but the Generic Specification assumes it to be satisfied if the loss of activity from a transport package is less than $10^{-6}A_2$ per hour following such an impact.

12 Typically the corner of another waste package.

Why is immobilisation needed during impact accidents and how is it achieved?

The release of activity from a waste package in response to an impact accident must be limited to ensure that the dose consequences of such a release is ALARP and within the relevant regulatory limits and targets.

Such releases will be in the form of 'mobile' radionuclides, in particulate or gaseous form, so the aim of the design of an encapsulated wasteform should be to limit the inventory of activity in these forms in a waste package. This will be achieved by ensuring that particulates associated with a waste are adequately immobilised by the waste conditioning process(es), that evolution of the wasteform maintains this immobilisation and that the wasteform can withstand mechanical impacts without generating excessive quantities of particulate.

Under compressive impact loading, a wasteform will generally deform in the vicinity of the impact (termed the 'knock back' zone) and be crushed spreading cracks into the main body of the wasteform. As the impact progresses, the volume of crushed material increases, generating particulates down to micron scale size. The fine particles of crushed wasteform could contain radioactivity. Based on this understanding, a key objective in designing a wasteform for acceptable impact performance is to minimise the quantity of particulate generated when the wasteform is deformed and also to minimise the quantity of particulate released from a deformed waste container.

Adequate immobilisation of radionuclides provided by an encapsulated wasteform is a key factor in ensuring that when subjected to the force of an impact accident, a waste package design will respond in a predictable and controlled manner, and any release of activity will be within acceptable limits. Inadequate immobilisation under impact accident conditions would result in the release of activity from a waste package and result in the requirements for the containment of radionuclides during transport, and/or radiation dose to workers, or members of the public, exceeding regulatory targets or limits.

The result of an impact accident is that the waste package will be significantly deformed, but the combined properties of the wasteform and waste container mean that the deformation has occurred in a controlled manner and release of particulate is minimised.

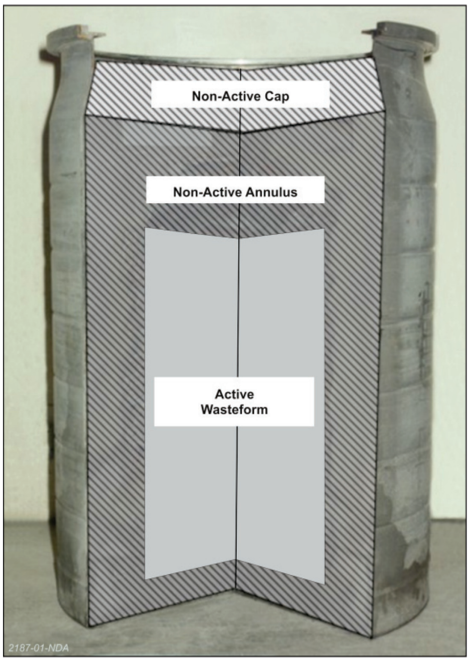
Immobilisation of particulate by the wasteform resulting in acceptable impact performance can be achieved by:

- Designing the wasteform with suitable physical properties including homogeneity, strength and fracture behaviour (i.e. the impact force does not cause the wasteform to shatter or crumble); and/or
- Designing the wasteform to minimise the extent to which the active wasteform crushes, thereby minimising the quantity of particulate material available for release (i.e. the use of a protective grout annulus and wasteform cap that will absorb the impact force and minimise the deformation of the active wasteform).

A wasteform design may include a layer of clean 'capping' grout on top of the active wasteform product [33]and/oran annulus of clean cementitious grout surrounding the active wasteform (Figure 5). Both of these design features can significantly reducing the volume of the active wasteform that would be crushed and reducing the generation of particulate activity. These features also increase the distance that particles must travel to allow their release, reducing the quantity of activity that could be released from the waste package.

The use of a grout annulus does have potentially significant implications for a waste conditioning process, including a more complex and costly wasteform production process; and a reduction in the effective volume of the waste container, which could result in the production of a larger number of waste packages. The design of a wasteform to achieve adequate immobilisation under impact accident conditions should therefore be initially based on the behaviour and performance of the active wasteform. If adequate immobilisation cannot be achieved by the active wasteform alone, then the addition of a non-active grout annulus to the wasteform design could provide a means of achieving acceptable waste package impact performance.

Figure 5 Schematic illustration of an 'annular grouted' wasteform



How is adequate impact accident performance demonstrated?

Determining the behaviour and performance of a wasteform and waste package design requires specialised testing and or modelling. Such work may include the following:

- Full-scale waste package drop testing;
- Finite element (FE) computer modelling combined with small-scale breakup test data; and
- Simple analogy to previously endorsed waste package designs with proven performance.

A detailed explanation of each of these methods is provided in [34].

5.1.3 Response to a fire accident

The requirement:

All reasonable measures shall be taken to ensure that, in the event of a fire accident, the quantity of potentially mobile radionuclides present within the waste package, including those generated as a result of the fire accident, is commensurate with the waste package meeting the impact accident performance requirements defined by the relevant WPS.

The wasteform should not readily burn or otherwise support combustion.

What is a fire accident?

In common with impact accidents, fire accidents which could occur during transport or following receipt of waste packages at the GDF are a potential mechanism for the release of radionuclides from waste packages into the environment where they can result in radiation dose to workers and members of the public.

The IAEA Transport Regulations [27] define limits on the release of activity from transport packages (which can be 'bare' waste packages or those transported in protective overpacks) under defined accident conditions of transport, which include a thermal challenge.

The OSC uses the BSLs defined by the SAPs as targets for the dose consequences of the release of activity from waste packages following accidents involving fires that could occur during the GDF operational period [29].

It is currently assumed that the bounding fire accident for unshielded waste packages during the GDF operational period is a fully engulfing fire with an average flame temperature of 1000°C and a duration of 30 minutes [35]. For shielded and robust shielded waste packages a fire duration of 60 minutes is currently assumed[13] [34].

Why is immobilisation needed during fire accidents and how is it achieved?

The release of activity from a waste package as a result of a fire accident will be of 'mobile' radionuclides in the form of particulate activity, radioactive gases and evaporated solid radionuclides. It is therefore important that the inventory of any materials that could contribute to any of these mechanisms is limited, such that the dose consequences of such activity release is ALARP and within regulatory limits and targets.

When a waste package is involved in a fire accident heat absorbed through its external surface is transferred into the wasteform predominately by thermal conduction and, to a lesser extent in encapsulated wasteforms, radiation. In the context of conduction the thermal diffusivity of a wasteform is important as it combines the thermal conductivity, density and specific heat capacity[14] of a material and gives a good indication of a material's response to heating. For example metals, which have thermal diffusivities one or two orders of magnitude greater than cementitious materials,heat up in a more uniform manner and their temperature will rapidly equalise to that of their surroundings.

There are various mechanisms by which radionuclides and particulate can become mobileand be released from within a wasteform as a result of heating:

- Some radionuclides, notably carbon-14, may react with air inside the waste package to form a gas which may then be released via the waste package vent.
- Some radionuclides(e.g. iodine) may be volatile and when heated may change phase to a gas which can then be released via the waste package vent.
- Heating of an encapsulated wasteform produced using inorganic or organic encapsulants can cause the generation of steam (for example produced from cement grout porewater) and other gases in greater quantities than produced under normal storage conditions. These gases may then be released via the waste package vent, carrying radionuclides and particulate activity with them.

Adequate immobilisation of radionuclides provided by an encapsulated wasteform is a key factor in ensuring that when subjected to a fire accident, a waste package design will respond in a predictable and controlled manner, and any release of activity will be within acceptable limits. Inadequate immobilisation under fire accident conditions would result in the release of activity from a waste package and result in workers or the members of public receiving radiation doses that exceed permissible limits.

The design and behaviour of an encapsulated wasteform is a key factor in ensuring that when subjected to a fire accident, a waste package will respond in a controlled and predictable manner, and any release of gaseous or particulate activity will be within specified limits. For waste packagesincorporating thin-walled waste containers immobilisation will tend to be provided by the physico-chemical properties of the wasteform. Specifically the thermal properties of the wasteform should be designed to minimise heating, by having a low overall thermal diffusivity.

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13 This value may be reduced when work currently underway is completed.

14 Thermal diffusivity$(\alpha) = k/\rho c_p$ where k is the thermal conductivity, $\rho$the density and $c_p$the specific heat capacity.

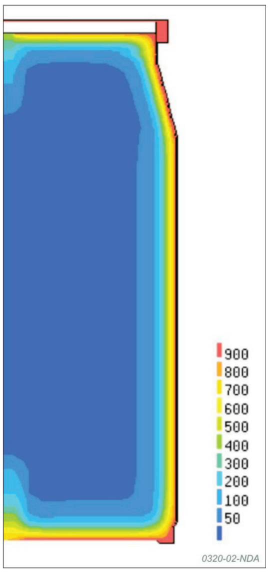
Cementitious grout has been shown to be a good material for limiting the heat reaching the waste if the waste package is exposed to a fire, possessing a number of advantageous properties, including:

- relatively high specific heat capacity (typically ~1000J $kg^{-1}K^{-1}$) which will limit the total temperature rise during a fire;
- low thermal diffusivity (typically of the order of $10^{-7}m^2s^{-1}$, which reduces further when the grout is dried out by the heat from the fire), which will limit the rate of temperature rise; and
- the presence of relatively large quantities of water associated with the cured grout which, when heated, can turn to steam, and remove a significant quantity of energy as latent heat,which would otherwise have caused the temperature of the wasteform to rise further.

Each of these properties will tend to reduce wasteform temperatures during a fire and, as a consequence reduce the release of activity from the wasteform and waste package.

Heat transfer through waste packages with cement encapsulated wasteforms is typically a slow and predictable process and the centre of the waste package may not experience its maximum temperature until several hours after the fire has been extinguished. Furthermore, because of the physico-chemical properties of the cement grout encapsulant, the bulk of the wasteform may not experience a significant increase in temperature. For example, Figure 6 illustrates the FE modelled behaviour of a typical 500 litre drum waste package containing a cementitious wasteform following exposure to a fire with a flame temperature of 1,000°C for one hour. It can be seen the thermal front does not extend further than ~100mm into the wasteform and that the bulk of the wasteform does not experience a temperature of more than 50°C. This illustrates the benefit that a non-active grout cap and/or annulus could provide in limiting the temperature of the active portion of the wasteform.

Figure 6 Temperature distribution in a 500 litre drum waste package at the end of a 1 hour fire



Cementitious grouts are not suitable encapsulants for all types of LHGW as they can chemically react with certain materials within the waste (e.g. metals). Organic polymers are very good at immobilising some challenging wastes such as reactive metals but are not so stable at high temperatures. To provide the same level of thermal performance, waste packages using polymer encapsulant wasteforms can include a grout cap and annulus to insulate the polymer wasteform against excessive heating and achieve acceptable fire performance.

In addition to the wasteform behaviour, the design and performance of the engineered vents in waste packages (or the gas permeable properties of concrete waste containers) will act to minimise the release of radioactive particulate entrained with the escaping steam or gas. Detailed guidance on the use and design of gas venting options is provided in [36].

How is adequate fire accident performance demonstrated?

Determining the behaviour of a waste package design requires specialised testing and or modelling. Such work may include the following

- Full-scale fire testing of a waste package;
- FE modelling combined with small-scale active furnace test data; and
- Simple analogy to other previous waste package designs with proven performance.

A detailed explanation of each of these methods is provided in [34].

5.1.4 Free liquids

The requirement

All reasonable measures shall be taken to exclude free liquids from the wasteform. This should include materials that may degrade to generate liquids. Free liquids not removed from wastes prior to waste packaging should be immobilised by a suitable waste conditioning process.

What is a free liquid?

A range of liquids are present in many ILW waste streams, including:

- specific organic or aqueous liquid waste streams (e.g. oils, solvents, cutting fluid and water based suspensions);
- streams containing cooling pond water, shielding water or other process liquors;
- liquid that is absorbed on a solid material such as cloth rags or zeolite;
- intricate solid wastes with free liquids trapped in interstices; and
- waste items such as pumps that may contain gearbox oil.

'Bleed water' can be produced as a by-product of cement grout encapsulation processes; as the solid grout material settles, water rises and will pool on top of the setting wasteform. Excess bleed water could remain in a waste package following curing unless steps are taken to remove it.

Following completion of the packaging process, water may enter the waste container via the lid joint or filter (e.g. during decontamination of the package external surfaces using high pressure water washing).

Liquid could be generated by the degradation of specific wastes within a wasteform during waste package evolution.

Why should free liquids be excluded?

The presence of free liquids implies incomplete immobilisation within a wasteform and such liquids may give rise to a number of undesirable effects within a wasteform, including:

- an increase in the mobility of radionuclides or toxic species in solution or suspension;
- an increase in the quantity of radioactive material released during normal and accident (i.e. impact and fire) conditions;

- an increase in the potential for chemical interaction between different waste components or between waste components and packaging;
- increased corrosion of components within the wasteform;
- increased inhomogeneity within the wasteform;
- increased microbial activity within the wasteform; and
- a reduction of the predictability of wasteform performance under normal and accident conditions.

How is the immobilisation of free liquids achieved?

Best practice in the conditioning of any waste is the elimination of free liquids and this applies particularly to wasteforms where voidage can exist and provide areas in which liquids can accumulate and/or be trapped.

Free liquids can be effectively eliminated by simple pre-treatment of the waste prior to packaging (e.g. by settling and draining) or by more aggressive techniques such as heating and/or the application of reduced pressure to encourage evaporation. Sealed vessels should be perforated and crimping of pipework during cutting should be avoided to reduce the possibility of trapped liquids.

In some cases, notably with liquids which are predominantly water, the liquid can be incorporated as part of formulation of a cementitious grout thereby forming part of the monolithic wasteform. This would normally require in drum mixing of the waste and grout and may also require need the liquid to receive some pre-treatment to ensure compatibility with the cement formulation (e.g. acidic liquors may need to be neutralised).

How is the immobilisation of free liquids demonstrated?

The immobilisation of free liquids in a wasteform can be demonstrated by testing at small and large scale (see Section 8), by reasoned argument or by analogy with other endorsed wasteform designs which possess proven properties and performance.

5.2 Mechanical and physical properties

The requirement:

The wasteform shall be designed to provide the mechanical and physical properties necessary to ensure appropriate performance of the waste package during all stages of long-term management.

Waste packages must have the mechanical properties necessary to enable their safe transport and handling and stacking during the GDF operational period. They will also need the properties that will ensure the necessary thermal performance and acceptable impact and fire accident performance.

Whatever mechanical and physical properties are required of a wasteform it is important that progressive evolution and degradation does not result in their premature loss. The required properties of the wasteform must to remain acceptable for a period of at least 150 years, as specified in the Generic Specification for waste packages containing LHGW.

5.2.1 Mechanical strength

The requirement:

The wasteform shall provide sufficient mechanical strength to allow the waste package to be transported and handled without affecting the ability of the waste package to meet all the requirements of the relevant WPS.

Why is wasteform mechanical strength required?

The requirement for wasteforms to possess 'sufficient mechanical strength' is a generic requirement aimed at ensuring that all waste packages possess adequate mechanical strength to withstand any forces to which they may be submitted under normal and accident conditions, without any loss of their ability to satisfy the needs of safe transport and disposal. Specifically a waste package needs to be sufficiently strong to withstand normal lifting and stacking forces, as well as those that could arise from accidents[15].

Most waste packages[16] are required to be capable of being stacked and bearing the loads that would result from being located at the bottom of a stack of waste packages of the same design, each with the maximum gross mass specified by the relevant WPS. For most of the standardised designs of waste container that are identified by the DSTS (i.e. for shielded and unshielded waste packages), these loads would be expected to be borne by the waste container alone. The exception to this is the 3 cubic metre drum in which the stacking feature is such that it relies on some support from the wasteform.

Progressive evolution and degradation of the wasteform over time is inevitable and this could result in a deterioration of the mechanical and physical properties of the wasteform. Wasteform strength must be shown to remain within acceptable limits over the required lifetime of 150 years to ensure acceptable waste package performance.

How is mechanical strength achieved?

The initial strength of an encapsulated wasteform is controlled by the chosen encapsulant and other factors such as the type of waste, waste loading, the conditioning process and the curing conditions used to produce the wasteform. Long term wasteform strength is controlled by a number of factors including interactions between the waste components and the encapsulant matrix, and waste package storage conditions (see Section 5.6).

How is mechanical strength demonstrated?

Wasteform strength is typically measured using compressive and tensile strength tests (see Section 8). Adequate wasteform strength may also be demonstrated by reasoned argument or by analogy with other wasteforms with proven properties.

5.2.2 Voidage

The requirement:

The development and production of the wasteform should ensure that the volume of voidage within the waste package (such as ullage, holes or other spaces) is appropriately minimised.

What is voidage?

Voidage, including macro-porosity[17], consists of discrete unfilled spaces within a wasteform. In an encapsulated wasteform voidage can result from incomplete mixing of the waste and encapsulant or the presence of sealed vessels or adventitiously closed sections of waste (e.g. sections of pipework with ends ‘crimped’ as a result of their being size reduced).

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[15] The requirement for a wasteform to contribute to the impact accident performance of the waste package is discussed in Section 5.1.2.

[16] The 500 litre drum waste package will be stacked in the GDF using stillages so that no load is imposed on the waste package itself.

[17] The term ‘macro-porosity’ as used here refers to voids visible without a microscope, with sizes of ~1mm and greater, and such as may have occurred as a result of incomplete mixing of a waste and an encapsulant. Micro-porosity, which can occur naturally during the curing of an encapsulant, is discussed in Section 5.2.3 under the heading of ‘porosity’.

Why is voidage a problem?

Examples of the possible adverse effects of voidage include:

- local corrosion of the waste container material and potential loss of container integrity;
- local corrosion of waste materials leading to the presence of mobile particles with a significant radionuclide content;
- reduction in wasteform and waste package strength;
- accumulation of flammable/explosive gas within voids;
- sites for the generation of other hazardous compounds (e.g. metal hydrides);
- long-term slumping/subsidence of waste packages in the GDF post-closure period; and
- the creation of connected voidage that could lead to enhanced leaching/migration of radionuclides from the waste package.

The presence of wasteform voidage also reduces confidence in the predictability of waste package performance under normal and accident conditions.

How is voidage reduced?

The usual approach adopted to achieve adequately low voidage in a wasteform is the use of an encapsulating medium with flow properties that maximise infilling of the waste whilst minimising gas generation while a wasteform cures. A wasteform cap can be used to minimise the ullage space that remains after a wastform has cured [33].

The actual consequences of voidage, in particular the magnitude of any related hazards, will depend on the nature of the waste, the wasteform and the container design. There may be specific wastes where, due to their physical and/or chemical properties, it may be difficult to completely eliminate the presence of voidage in the manufactured final wasteform. It may also be the case that a degree of voidage in a wasteform may have little or no consequence to the performance of the waste package. For packaging proposals involving such wasteforms, reasoned arguments can be made as to why the need to eliminate voidage is unnecessary.

Some wastes (e.g. filters) present particular challenges in the minimisation of voidage and specific guidance is available [16].

How is adequate voidage reduction demonstrated?

Minimisation of voidage is typically demonstrated by reasoned argument, supported by an application of the principles of best practicable means and BAT, by the visual inspection of sectioned wasteforms, or by analogy with other wasteforms with proven properties.

RWM are currently engaged in work to quantify what constitutes an acceptable level of voidage within a waste package. This work may enable a ‘screening level’ to be defined for the allowable voidage in different types of waste package. In the meantime the issue voidage in proposed waste packages will be considered on a case by case basis as part of a disposability assessment.

5.2.3 Mass-transport properties

The requirement:

The wasteform shall be sufficiently permeable to allow gases generated within the wasteform to be released without compromising the ability of the waste package to meet any aspect of the relevant WPS.

The mass transport properties of the wasteform (e.g. diffusivity and permeability) shall provide best practicable means for the containment of water-soluble radionuclides within the waste package.

The wasteform provides the primary containment function for radionuclides within a waste package, and the first barrier to radionuclide migration within the geological disposal system. For encapsulated wasteforms the physical properties of the waste and any encapsulant will control the effectiveness of the containment and the rate of migration of soluble radioactive species. The key wasteform properties in this respect are permeability to fluids (i.e. gases and liquids), diffusivity, and porosity.

The porous and inhomogeneous nature of most LHGW wasteforms, and the thermodynamic equilibrium approach taken to modelling their performance under GDF conditions, means that their leaching performance is not a relevant property. As a consequence the Wasteform Specification includes no explicit requirement for the leachability of LHGW wasteforms. However, the IAEA Transport Regulations make a special case for the leachability of low specific activity (LSA) material with the highest permitted activity concentration (i.e. LSA-III), and it is therefore mentioned in this context.

a) Permeability

Permeability defines the rate of fluid movement through a porous medium under an applied pressure head. A wasteform with low permeability will normally contribute to the containment of radionuclides by restricting the movement of water within it. However, a wasteform with a very low permeability may be susceptible to pressurisation by internally generated gases. A range of processes, including the corrosion of components of the waste (notably of reactive metals), radiolysis and biodegradation can generate gas within a wasteform. If gas is generated more rapidly than it can move through a wasteform matrix, the pressure within a wasteform will increase and, if it exceeds the tensile strength of the matrix, cracking and spalling can occur. Such evolution of the wasteform can affect the immobilisation of radionuclides and reduce the mechanical strength of the wasteform. Therefore the gas permeability and strength of the wasteform should be such to ensure that internal pressurisation does not result in an unacceptable loss of performance. Overall, a balance must be maintained to ensure the overall waste package performance is not compromised by this aspect of wasteform performance.

b) Diffusivity

The diffusivity of a material describes the rate of migration of solutes under a concentration gradient. When expressed as a diffusion coefficient it takes account of the retardation of solutes by interaction with solid surfaces. Prior to disposal and in the early evolution of a GDF, there is unlikely to be a water pressure head, so the diffusion of radionuclides is the only mechanism for migration. Therefore low diffusivity contributes to containment, preventing the spread of radionuclides into inactive regions of the wasteform, notably a grout cap or annulus.

c) Porosity

Porosity is the amount of microscopic open space in a material, and includes both closed and inter-connected pore structures. The shape and size of the pore structure (its morphology), rather than its total value, is related to permeability. This relationship can vary significantly, for example large pore voids connected by narrow pore throats is likely to yield a low permeability structure, whereas a very uniform pore structure may yield a higher permeability, even if the total porosity is significantly lower. Broadly speaking, the more porous an encapsulated wasteform, the weaker and the less durable it will be and the greater its ability will be to retain liquids.

d) Leachability (LSA-III material only)

In the context of wasteform performance, leachability can be defined as the rate of release of soluble constituents of a wastform, including radionuclides, into water percolating through it.

The specific requirement for wasteforms that are to be classed as LSA-III material, and which are to be carried in Type IP transport packages, is (Paragraph 226):

> *'The radioactive material is relatively insoluble, or it is intrinsically contained in a relatively insoluble matrix, so that, even under loss of packaging, the loss of radioactive material per package by leaching when placed in water for seven days would not exceed* $0.1A_2$*'.*

The purpose of this requirement is to justify the higher specific activity (i.e. $2 \times 10^{-3} A_2 g^{-1}$) for LSA-III material[18]. The advisory material that supports the IAEA Transport Regulations describes the purpose of the leaching test as being to *'… demonstrate sufficient insolubility of the material when exposed to weather conditions like rainfall.'* [37].

How can suitable mass transport properties be determined and demonstrated?

Encapsulated wasteforms should be designed with mass transport properties that contribute to the containment of radionuclides within the waste package. This means that the encapsulant should have a permeability/porosity relationship that is consistent with restricting fluid transport, but which prevents over-pressurisation, and a diffusivity that restricts early migration of radionuclides into inactive parts of the wasteform.

In general, the demonstration that a wasteform has suitable mass transport properties would be by a combination of wasteform development work (see Section 6) and analogy with previous wasteform development work for similar waste/encapsulant combinations.

It is possible to measure the gas and water permeability of waste materials, grouts or simulated wasteforms by established methods. In practice, however, it is more usual to demonstrate suitable mass transport properties by reasoned argument based on published data for common materials, by analogy with other wasteforms with proven properties, and/or by empirical evidence of wasteform stability to internal gas generation.

The total porosity of a wasteform, and its morphology, can be controlled by careful design and manufacture of materials. Both cementitious and polymeric encapsulants are naturally porous, the extent of which will depend on the physical and chemical properties of the grout, and the process conditions, notably the mixing and curing regimes. In the case of cementitious grouts this natural porosity will depend on the ratio of water to cement in the original mix, and typically lies in the range 10-20%. Additional porosity could be created by gas generating reactions between the waste and the grout and the potential consequences of this this should be considered during wasteform development work.

A regime for the conduct of an assessment of the leachability of wasteforms to be classed as LSA-III material is defined in Section VII of the IAEA Transport Regulations.

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[18] This being a factor of 20 higher than that for LSA-II material (Paragraph 409).

5.2.4 Homogeneity and heterogeneity

The requirement:

Local concentrations of materials within the wasteform, that may compromise the ability of the waste package to meet any aspect of the relevant WPS, should be minimised.

What is homogeneity and why is it important?

Lack of homogeneity in a wasteform may undermine the steps taken to engineer particular properties of the wasteform in order to address other performance criteria. Heterogeneity may also reduce confidence in the predictability of waste package performance under normal and accident conditions.

Lack of homogeneity and uniformity within a wasteform may arise due to the following factors:

- packaging of diverse wastes;
- the presence of hollow or sealed objects (i.e. voidage, see Section 5.2.2);
- the flotation of low-density wastes such as plastics and wood;and
- the accumulation of high-density wastes such as metals at the bottom of the container.

The actual consequences of excessive heterogeneity, in particular any hazards arising from, or enhanced by, such heterogeneity will depend on the nature of the waste, the wasteform and the container design. Examples of the possible effects of significant heterogeneity include the following:

- High concentrations of radionuclides can lead to:
    - areas of high waste package external dose rate;
    - reduced predictability of waste package performance under impact and fire accident conditions;
    - undermining of the assumptions underpinning the criticality safety assessment of the waste package (i.e. from local concentrations of fissile material);
    - excessive localised gas generation by radiolysis; and
    - localised radiogenic heating of the wasteform leading to thermal stresses.
- High concentrations of reactive metals can lead to the mechanical integrity of the wasteform being compromised as a result of localised expansive corrosion;
- Variations in the mechanical and physical properties of the wasteform (e.g. thermal conductivity, permeability)
- Areas containing low strength materials, such as organic materials, or discontinuities in the wasteform such as cracking or poor bonding planes, which may make the wasteform weaker and so more susceptible to damage in the event of an accident;
- Local concentrations of specific waste materials which create chemical conditions that could accelerate waste and waste container degradation by chemical and microbial mechanisms.

How can adequate homogeneity be achieved?

It is best practice to design a wasteform in a manner that will inherently promote homogeneity and minimise heterogeneity. This can be easily achieved for fluid waste streams (i.e. liquids, sludges and slurries) by mixing the waste, either within or outside of the waste container, with a suitable encapsulant. Pre-treatment of heterogeneous wastes can be used to improve homogeneity (e.g. the removal of pieces of fuel or activated components such as nimonic springs from Magnox fuel element debris). Other potential approaches to promote homogeneity include:

- separation of waste types;
- opening/puncturing of hollow or sealed items;
- size reduction of large flat objects; and
- careful wasteform design to prevent cracking.

How is homogeneity demonstrated?

Homogeneity can be demonstrated by chemical analysis of a wasteform and or visual inspection of a sectioned wasteform. Reasoned arguments, based upon description of the waste and the packaging process, and the likely properties and performance of the wasteform, can also be used to demonstrate that adequate homogeneity has been achieved.

5.2.5 Thermal conductivity

The requirement:

The thermal conductivity of the wasteform shall be sufficient to dissipate any heat generated within the waste package, when emplaced in a GDF, without unacceptable temperature rise.

What is thermal conductivity and why is it important?

Thermal conductivity is a measure of the ability of a material to conduct heat and thereby distribute heat energy. The effective thermal conductivity of a wasteform will therefore influence the temperature that a waste package attains during the all stages of long-term management, particularly following emplacement in a GDF, and the distribution of temperatures that would result from a fire accident. The design of the GDF disposal vaults will take account of the thermal properties of the waste packages, notably thermal conductivity, along with those of other GDF engineered barriers such as the vault backfill and the thermal properties of the host rock.

Depending on the geological setting of a GDF, a large proportion of the backfilled disposal vaults could be occupied by cementitious materials, which would have a major influence on the temperatures that will be attained in the long term. Such materials typically have thermal conductivities in the range 0.50 to $0.77 Wm^{-1}K^{-1}$ [38] and these values are used in the thermal modelling of backfilled disposal vaults [39, 40]. The modelling considered the consequences of waste package thermal conductivities in the range 0.5 to $5 Wm^{-1}K^{-1}$ and this showed that the lower value would not be expected to adversely affect the overall thermal performance of the vaults. This value (i.e. $0.5\ Wm^{-1}K^{-1}$) is therefore used as a guidance value for the minimum thermal conductivity of wasteforms.

With regard to an upper limit for wasteform thermal conductivity, the work reported in [40] shows a relative insensitivity of the thermal performance of the backfilled vaults to wasteform thermal conductivities of up to $\sim 10\ Wm^{-1}K^{-1}$. However, other aspects of wasteform thermal behaviour, in particular fire performance (Section 5.1.3), may be adversely affected by higher wasteform thermal conductivity.

How can thermal conductivity be determined and demonstrated?

Several methods are available for determining the thermal conductivity of a wasteform [41]. Steady-state methods are suitable for measuring the thermal conductivity of cemented wasteforms over a range of temperatures representative of those expected in a GDF. The type and composition of each waste needs to be considered in order to define the most appropriate method. For heterogeneous wasteforms, small-scale experiments may not be suitable as they may not be large enough to eliminate any anisotropic heat conduction effects that could be created by the presence of large waste items. For homogeneous wasteforms, simple small-scale experimental methods can be used; these methods are described in [42].

Acceptable thermal conductivity may be demonstrated by test results on wasteform samples, by reasoned argument or by analogy with other endorsed wasteform designs with proven properties.

5.3 Chemical containment

The requirement:

The wasteform shall not be incompatible with the chemical containment of radionuclides and hazardous materials as embodied in the requirements of a GDF.

Where they may affect chemical containment, the following items should not be introduced through waste conditioning or packaging, and their presence in wastes should be minimised wherever practicable:

- ***oxidising agents;***
- ***acids and/or materials that degrade to generate acids;***
- ***cellulose and other organic materials;***
- ***complexants and chelating agents, and/or materials that degrade to generate such compounds;***
- ***non aqueous phase liquids (NAPLs) and/or materials that degrade to generate them;***
- ***any other materials that could detrimentally affect chemical containment.***

What is chemical containment?

For many designs of GDF, depending on the geological setting, the near-field engineered barrier will be provided by the vault backfill, which will be formulated to limit the migration of radionuclides during the post-closure period. The long-term performance of the GDF will therefore rely on the backfill fulfilling its design functions and the compatibility of waste packages with the achievement of this requirement.

In general the backfill will be designed to create and sustain an alkaline environment in which the solubility of many key radionuclides will be reduced and the corrosion rates of steels will be minimised. The backfill material would also be designed to be porous with a large surface area to increase the sorption of many radionuclides, and to allow dispersal of any gas generated within the disposal vaults without causing over-pressurisation and cracking. For many radionuclides, including several with long half-lives, from the transition metal, lanthanide and actinide series, solubility at high pH is low and sorption to cementitious materials is high. This forms the basis for restricting the rate at which radionuclides can migrate from the GDF near-field; it is therefore desirable that the high pH conditions and sorption capacity of the backfill persist for as long as possible.

Waste packages containing cement encapsulated waste can make a contribution to the chemical containment of the GDF near-field and the benefit of this contribution can be claimed in the design of the GDF, such as allowing a reduction in the quantity of backfill that will be needed. For waste packages containing waste encapsulated using other materials (e.g. polymers) the only contribution to chemical containment is that which may be made by the waste, which may be very small. In such cases the priority is then to minimise the quantities of materials that may have a deleterious effect on chemical conditioning.

How can adequate chemical containment be achieved?

Where possible, the design and long term behaviour of a waste package, notably the wasteform, should avoid degrading the effectiveness of the backfill, and minimise the requirement for an increased quantity of backfill material to be provided. The ultimate solution is to prevent materials that could have a deleterious effect on the backfill from escaping from the waste package at all, by providing physical containment in the form of the waste container. However, the long timescales over which such containment would be required (i.e. into the post-closure period), and the fact that many designs of waste container are vented, makes this impractical in most cases. Best practice is therefore to limit the impact of the wasteform on the backfill by minimising the content of materials that could contribute to increased radionuclide solubility and/or a reduction of backfill pH. Guidance on these issues is provided below.

a) Maintaining a high pH environment

Whilst it is the case that many types of raw waste are slightly alkaline, a number of common organic materials such as cellulose (e.g. paper, wood and cotton) can degrade by alkaline hydrolysis to form acidic species and the degradation of materials such as PVC by radiolysis can produce hydrochloric acid. These acids could react with the backfill and reduce its pH buffering capacity.

The waste packager should aim to design a wasteform which does not compromise the ability of the backfill to provide a high pH environment, and it is preferable that a wasteform containing long-lived radionuclides is able to contribute to the maintenance of high pH buffering within the package. The use of inorganic cement based encapsulants is the preferred method for maintaining conditions of high pH within a wasteform.

A factor controlling the pH generated by inorganic cements is the calcium to silicon atomic ratio (Ca/Si) of the overall cementitious composition of the disposal vault. The use of cementitious immobilising matrices with low Ca/Si ratio, beyond the values assumed for post-closure modelling of the GDF, may require reappraisal of the quantity of backfill material to be used in a GDF. Therefore, waste packagers are encouraged to use a cementitious immobilising material with a high Ca/Si ratio wherever feasible. The minimum acceptable effective Ca/Si ratio of the wasteform is dependent upon the waste type and radionuclide content and is considered on a case-by-case basis during the disposability assessment of a packaging proposal.

The requirement to maintain the high pH of the backfill does not preclude the disposal of organic wastes or the use of polymer and vitrified glass wasteforms; the use of such wasteforms will be considered as part of the disposability assessment of proposals to adopt such approaches. RWM continues toresearch the use of such materials and has produced guidance on the use of such materials [43].

b) The effects of organic materials and complexant species

Organic materials present in a wasteform could have a significant effect on the post-closure migration of radionuclides from a GDF. The degradation of organic materials present in some wasteforms (e.g. cellulose waste materials) has been shown to produce chemical species that act as complexants. Complexants can increase the solubility of some radionuclides, including plutonium, and reduce the sorption capacity of the backfill and the geological barrier.

It would be impractical to eliminate all organic materials from a GDF, but wherever possible the quantity of cellulose in waste should be minimised to restrict the potential for complexant generation. Work has shown that a cellulose concentration of less than ~20kg per cubic metre of a cement based wasteform should not cause any concerns with regard to the production of radionuclide complexants. The potential implications of specific packaging proposals for the disposal of cellulose waste on GDF post-closure performance are evaluated during the disposability assessment of a packaging proposal.

c) The presence of non-aqueous phase liquids (NAPLs)

NAPLs are organic liquids, such as oils and solvents, which have limited miscibility with water. They are known to be present in the many ILWwaste streams and may also be created in waste packages following disposal, principally as products of radiolysis of organic polymers and the putrefaction and microbial degradation of cellulose or other polymeric/organic materials.

If present in sufficient quantity, low density[19] NAPLs could become mobile due to their buoyancy, providing a pathway for the migration of dissolved radionuclides through the geosphere towards the biosphere. Small NAPL droplets could contribute directly to radionuclide migration by the groundwater pathway as a form of colloidal transport. NAPLs also have the potential to affect the surface properties of solids with which they come into contact, and therefore have the potential to affect the sorption properties of the backfill, other near field materials and the geosphere. As well as potentially affecting the transport of radionuclides, many NAPL-forming compounds are themselves toxic and these compounds have been considered in toxicity assessments. RWM continues toresearch the consequences of the presence of NAPLs in the GDF and has produced guidance on the control of such materials during the packaging of waste [44].

How can chemical containment be demonstrated?

The concentrations of materials with significance to chemical containment in waste should be minimised prior to waste package manufacture. An essential part of the demonstration is the presentation of accurate and reliable information on the waste stream inventories of those materials that could jeopardise chemical containment in the GDF (cellulose, NAPLs etc.). Reasoned arguments about the potential effects of such materials on chemical containment typically form another part of the demonstration.

Where necessary the ability of a wasteform to retain such materials could be demonstrated using a leach test.

As noted above, the waste container will provide physical containment of materials that could deleteriously affect the chemical containment properties of the GDF near-field, albeit for a limited period. The benefit of this containment can be claimed if underpinned by arguments regarding the expected durability of the integrity of the waste container.

5.4 Hazardous materials

The requirement:

The wasteform shall not contain hazardous[20]materials, or have the potential to generate such materials, unless the treatment and packaging of such materials or items makes them safe. The means by which any of these materials is made safe shall be demonstrable for all relevant periods of long-term management.

What are hazardous materials and why are they important?

Radioactive wastes contain a wide variety of materials, some of which, because of their chemical and/or physical nature, create additional hazards during packaging, transport and disposal. The elimination of such materials from waste packages, or their treatment to render them less hazardous, is an important factor in ensuring the passive safety of waste packages.

Such materials may exist at the time of packaging, and further hazardous materials (e.g. organic molecules and gases) may be produced from the degradation of the waste, the materials used for conditioning and packaging, or by reactions between them. The

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[19] i.e. less than that of water.

[20] Including flammable, explosive, pyrophoric, chemo-toxic and oxidising materials; sealed and/or pressurised containers; and/or mechanical devices containing stored energy.

transport and handling of all such materials will be subject to the appropriate regulations as well as a general duty of care. Consequently, the potential presence or generation of such materials will have to be taken into account during the design of a waste package.

Some objects contained in wastes may constitute a hazard because of their physical state, as distinct from a chemical hazard. Examples of this category of hazardous material are wastes that include pressurised and/or sealed containers. The removal of such items or their treatment to remove hazardous properties may be necessary in order to ensure a safe and stable wasteform.

The following sub-sections discuss specific types of hazardous materials in more detail. It should be remembered that some waste materials involve more than one type of hazard.

a) Pyrophoric materials

Pyrophoric materials are materials that are liable to oxidise rapidly when exposed to air with an accompanying increase in temperature, sometimes to the extent of combusting spontaneously. They are typically metals, or mixture of metals with their oxides, in a finely divided form. Particular examples are finely divided uranium, thorium and plutonium metal, and other examples include uranium hydride and phosphorus.

The presence of pyrophoric materials in a waste package presents an increased hazard by providing a potential ignition source for combustible waste and increases the possibility of sustained combustion. They also provide a potential source of ignition for flammable gases such as hydrogen which may be generated within the wasteform.

b) Oxidising materials

Oxidising materials are defined as those which exhibit highly exothermic reactions, or form unstable compounds, when in contact with other substances, particularly flammable substances. Oxidation reactions may produce gases which could increase the pressure within the waste package (see Section 5.5). The presence of oxidising materials increases the potential for fire, as they provide a source of oxygen to combustible material. The presence of both types of material in the same waste may therefore compromise the benefits of a conditioning process that seeks to render the waste non-combustible by excluding atmospheric oxygen.

Examples of oxidising materials include peroxides, chlorates and nitrates.

c) Flammable materials

Flammability hazards are subdivided into highly flammable and flammable.

Highly flammable materials include the following:

- Liquids having a flash point below 21°C (which may therefore catch fire at ambient temperature);
- Gaseous substances that are flammable in air at room temperature; and
- Substances, such a metal carbides and hydrides, which in contact with damp air or water evolve highly flammable gases.

Flammable substances are defined as liquid substances or preparations with a flashpoint ≥21°C and ≤55°C. Flammable gases can arise from several sources. The most common gas generated by ILWwill be hydrogen;as a result the radiolysis of water and organic materials, by the reaction of metals such as aluminium, magnesium and zinc with cement grout, and/or by the reaction of hydrides with water that is free or bound within the wasteform. Carbides present in wastes may react with free or bound water to generate acetylene, methane and ethane. Methane may also be generated from anaerobic microbial degradation of organic material, particularly putrescible material.

d) Explosive materials

Explosive materials are defined as those which may explode under the effect of flame or which are more sensitive to shocks or friction than dinitrobenzene. The potential for explosions and the resulting dispersal of activity from a waste package during interim storage, handling and transport represents a risk of injury and/or increased doses to workers and the public, and may cause damage to plant, safety systems and other waste packages.

The assessment of any explosion hazard must take account of situations where combinations of substances within a waste have the potential to generate explosive materials. A notable example of this would be a combination of organic materials, such as cellulose, and acids, or materials that degrade to release acid or a combination of ammonium nitrate with a fuel source.

Other examples of explosive materials that may be present in LHGW include boron hydrides and lead azide.

e) Sealed and/or pressurised containers

The presence of sealed and/or pressurised containers within a wasteform would represent a significant increase in risk of damage to the wasteform and breaching of the waste package. Typical examples of pressurised containers are gas cylinders, aerosol cans, components of compressed air systems and reservoirs.

Release of the stored energy by catastrophicfailure of a pressurised container could result in a breach of the waste container and dispersal of the waste package contents. During handling operations associated with interim storage and transport this would represent a risk of injury, increased dose to workers, and possible damage to safety systems and other waste packages. Less energetic failures could result in localised damage to the wasteform and/or waste container, and an associated loss of integrity. Additional hazards could also be presented by the released contents of the container if they are hazardous in their own right. Sealed containers that were not pressurised at the time of packaging could nonetheless become pressurised as a result of gas generation due to corrosion, radioactive decay (e.g. of radium to form radon) and/or radiolysis. The presence of sealed containers in wasteforms could also compromise the requirement to minimise voidage (Section 5.2.2).

How can adequate consideration of hazardous materials be demonstrated?

The nature and magnitude of a hazard will depend on the nature of the waste, wasteform and packaging methods. During the development of a packaging proposal, the waste packager should demonstrate that these materials have been considered, and that they will be removed or their hazardous properties eliminated. Hazardous materials may include pyrophoric or explosive materials, in which case it will be necessary to demonstrate that such materials have been rendered safe; more specifically, it will be necessary to demonstrate that the resulting waste package will comply with the assumptionsunderpinning the transport and operational safety cases.

5.5 Gas generation

The requirement:

Gases generated by the wasteform shall not compromise the ability of the waste package to meet any aspect of the relevant WPS.

What is gas generation and why is it important?

A wide range of gases can be produced by and released from wasteforms as a result of corrosion of reactive metals, degradation of organic materials, radiolysis of water and radioactive gas generation. The principal non-active gases (in volume terms) are H_2, CO_2, CH_4 and H_2S. For wastes containing significant quantities of α-emitting radionuclides, the generation of helium can also contribute to the total quantity of gas generated. Each of these gases may be labelled with tritium and/or carbon-14. Bulk gas releases may also carry any smaller quantities of other radioactive gases such as radon-220, radon-222, argon-41 or krypton-85 which may be present in the waste.

The potential issues resulting from gas generation are:

- the release of radioactive, flammable or toxic gases from the waste package;
- pressurisation of the waste container; and
- pressurisation of the wasteform.

If gas is generated more rapidly than it can move through a wasteform matrix, the gas pressure within a wasteform will increase. If the gas pressure exceeds the tensile strength of the wasteform matrix, cracking and spalling of the matrix can occur, and this can affect the immobilisation capacity and mechanical strength of the wasteform. Most cement based wasteforms are expected to have sufficient gas permeability to allow gas to be released from the wasteform without significant degradation of the matrix [14].

Detailed guidance on waste package related gas generation issues is provided for unshielded packages in [8] and for shielded packages in [9]. This section provides guidance on the gas generation processes and gas pressurisation degradation mechanism that are specific to encapsulated wasteforms.

a) Gas generation by corrosion

The rate of hydrogen generated by corrosion of metal under anaerobic conditions can be estimated from the following equation:

$$V = k_1 A\rho S/M$$

Where: V is the volume of hydrogen gas generated in litres/year;
k_1 is a constant (the volume of 1 mole of gas at STP; 22.4 litres);
r is the corrosion rate in μm/yr;
A is the corroding area in m^2;
ρ is the density of the metal in kgm^{-3};
M is the atomic weight of the metal in g; and
S is the stoichiometry of the reaction[21].

Table 1 lists simplified versions of this equation from which estimates of hydrogen generation may be determined for metals commonly found in ILW, and using representative values for r and A.

Table 1 Gas generation rates of selected metals by corrosion

Metal	Gas generation rate (litres/day)
Aluminium	$9.2\text{x}10^{-3}$ rA
Magnesium	$4.4\text{x}10^{-3}$ rA
Mild steel	$8.6\text{x}10^{-3}$ rA
Uranium	$9.9\text{x}10^{-3}$ rA

The encapsulation of metals in cement can be used to control the environment to which a metal is exposed (e.g. pH, relative humidity and water availability).

[21] The number of moles of hydrogen generated by the corrosion of 1 mole of metal.

In general, gas generation by the corrosion of metals can be minimised by limiting the quantity of water present in a wasteform.

b) Gas generation by radiolysis

The rate of gas generation by the radiolysis of materials within a wasteform can be estimated from the following equation:

$$V = k_2 G Q$$

Where: V is the volume of generated in litres/day;
k_2 is a constant (which has a value of 0.22 at STP for the units used);
Q is the heat output in watts for the volume of wasteform in question; and
G is the 'G-value'[22] for a given gas produced from the radiolysis of a given material.

c) Gas generation by the microbial degradation of cellulose and other organic materials

The biodegradation of cellulosic material, whichgives rise to the production of CO_2 and CH_4, is the most important microbial process because the degradation of other organic materials (e.g. plastics and rubber) is likely to be very much slower and hence not make a significant contribution to the overall rate of gas generation. Further detailed guidance on the mechanisms of gas production from the degradation of organic materials is provided in [45].

d) Radioactive gases

Some metallic wastes (e.g. fuel cladding) contain tritium, either combined as metal tritides, or in the form of tritiated hydrogen which has diffused into the metal surface. These are usually 'hard' wastes (i.e. diffusionally thick solids) which have been tritiated at above ambient temperatures for extended periods of time. For tritium in these forms, the release rate is dependent on the corrosion rate and/or the rate of diffusion of tritium from the material.

Tritium is also present in wastes as tritiated water, most usually in 'soft' laboratory-type wastes which are predominantly papers, tissues and other diffusionally thin materials. Tritiated water may become involved in corrosion processes and thus be converted to tritiated hydrogen or released by evaporation. Thus, the corrosion rate is important, together with the quantity of tritiated water associated with the waste, and its accessibility to potential corrosion sites. Tritium-labelled methane and hydrogen sulphide may also be formed from microbial action on organic materials if tritiated hydrogen or tritiated water is involved in the reactions. Guidance on this issue can be found in [21].

Other radionuclides can be incorporated into other gaseous molecules by microbial action. Methane and carbon dioxide labelled with carbon-14 are the principal gases expected from this source and hydrogen sulphide may be generated under anaerobic conditions. The ratio of stable nuclide to radioisotope (e.g. organic carbon-14 to carbon-12) is important in determining the extent of generation of the radioactive gas, taking into account the chemical form of the radioactive material and isotopic exchange.

Owing to their half-lives (i.e. 12.3 years for tritium and 5,730 years for carbon-14) it is unlikely that hold-up offered by transport through any wasteform would offer sufficient decay to significantly reduce releases of these two radionuclides in gaseous forms prior to disposal unless sufficient isotopic exchange occurred. However, reductions in the generation rates for their inactive analogues would lead to corresponding reductions in the release of radionuclides.

Some wastes produce radon isotopes notably from the radioactive decay of actinides. Radon-220 and radon-222 occur naturally in the decay series of thorium-232 and uranium-

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[22] An experimentally determined value expressed in molecules produced per$1.6\text{x}10^{-15}$J (100ev) of energy absorbed.

238 respectively. In addition, concentrated sources of uranium-232 and radium-226, producing radon-220 and radon-222 respectively, may be present in some wastes.

The half-lives of radon-220 and radon-222 are relatively short (i.e. 55.6 seconds and 3.82 days respectively) and discharges of radon from waste packages can therefore be significantly reduced by wasteforms that provide containment and/or hold-up to permit decay and the retention of the decay products within the waste package. Further guidance on this issue can be found in [19].

How are gas production rates demonstrated?

Gas production rates from waste package during transport and the GDF operational period can be determined using the approaches discussed above or by the use of a suitable modelling tool.

5.6 Wasteform evolution

The requirement:

Changes in the characteristics of the wasteform as it evolves shall not result in degradation that will compromise the ability of the waste package to meet any aspect of the relevant WPS.

The deleterious effects of the following processes should be considered:

- ***dimensional changes, e.g. shrinkage;***
- ***corrosion including, but not limited to, the production of gases and particulate material, and wasteform expansion resulting from the formation of lower density solid corrosion products;***
- ***microbial activity;***
- ***self-irradiation and irradiation by surrounding waste packages;***
- ***heat generation by the wasteform and its surroundings including, but not limited to, localised heat sources within the wasteform, the effects on the curing of the encapsulant material and the consequential effects on longer-term performance.***

What is wasteform evolution?

The physico-chemical properties of a wasteform will evolve over time due to a variety of processes such as the radiolysis, biodegradation of the waste and/or conditioning materials, corrosion of metals in the waste mineralogical changes (e.g. carbonation) of cementitious materials. The rate, extent and significance of any physico-chemical changes from evolution are very wasteform specific and will depend on thenature, quantities and forms of materials present within a wasteform andthe environmental conditions that a wasteform is subjected to, including saturation by ground water during the GDF post-closure phase.

The role of the encapsulated wasteform is to behave in a benign and predictable manner during all stages of the waste package disposal process. The packaging specifications require that the evolution of a wasteform over a period of 150 years will not result in any significant changes to the properties of a waste package such as would result in non-compliance of a package with the safety cases for transport and the GDF operational and post-closure periods. Therefore all potential changes to the physico-chemical properties of a wasteform over time must be identified and evaluated and, if such changes are significant; their potential effects on waste package performance must be understood and shown not to affect the safety of the long-term management of the waste.

Further detailed information on the processes that result in wasteform evolution and their potential effects is provided in [14].

The Wasteform Specification [6] identifies the wasteform evolution processes and effects to be considered; guidance is provided in the sections below.

a) Dimensional stability

Wasteforms will be subject to physical or chemical processes that may result in dimensional changes, either by swelling or shrinkage. Significant dimensional changes can lead to a reduction in the immobilisation provided by a wasteform (e.g. by cracking and the formation of particulates), or result in the degradation of a wasteform by other processes (e.g. the cracking of a cementitious wasteform will increase the surface area of material available for carbonation etc.).

The swelling of a wasteform can occur by expansive phase reactions or by excessive radiolytic damage to a polymer encapsulant. Expansive phase reactions which result in significant swelling of a wasteform occur due to reactions between the waste and encapsulant, either directly (e.g. corrosion of aluminium in a high pH environment) or indirectly due to the presence of aggressive chemical species. For example, degradation of phenol formaldehyde-type ion exchange resins can produce sulphate ions which can react with a cement matrix and form expansive mineral phases such as ettringite and thaumasite.

Shrinkage is typically associated with cementitious wasteforms due to ongoing cement hydration of reactions or the loss of porewater by drying.

b) Corrosion of reactive metals

Reactive metals, such as aluminium, Magnox and uranium will corrode in the presence of the alkaline porewater of a cement encapsulant. The corrosion of metallic wastes will generally result in products with a lower density and expansion of the waste, typical volumetric expansion factors are listed in Table 2.

Table 2 Expansion factors for reactive metals found in ILW

Metal	Corrosion product	Volumetric expansion factor	Guidance value for the mass of uncorroded metal in a waste package (kg)	
			500 litre drum	3 cubic metre box and drum
Aluminium	$Al(OH)_3$	3.2	3.7	22
Iron	Fe_3O_4	2.1	22	130
Magnesium	$Mg(OH)_2$	1.8	6.7	40
Uranium	UO_2	2.0	5.9	35

The growth of expansive corrosion products on the surface of waste metal can cause stress on the wasteform matrix; ultimately the stress may eventually overcome the tensile strength of the matrix and lead to wasteform cracking. If the cracking is extensive, it can affect the immobilisation capability and mechanical strength of the wasteform. Table 2 lists guidance quantities for the four metals that could be packaged in unshielded waste packages without leading to a volumetric expansion of greater than 2000ppm, a value that has been shown not to threaten the integrity of a cement based wasteform.

If the increase in the volume of a waste material is sufficient, this can also impose a stress on the waste container. Depending on the mechanical properties of the container this could result in deformation, or possibly rupture [14].

The corrosion of metals (and some other materials) can result in the creation of active particulate that could be released from the waste package under accident conditions. Corrosion can also result in the release of active gases (notably tritium) entrained in metallic wastes.

In some instances contact between dissimilar metals, which may be between metals in the waste and the waste container itself, can result in accelerated corrosion rates as a result of galvanic coupling [14].

c) Microbial and radiolytic degradation

Polymer encapsulants and organic wastes in particular can undergo radiolytic, chemical, thermal and microbial degradation. Degradation of specific materials present in wasteforms can generate chemical species that have the potential to react with container materials (e.g. stainless steel and concrete) and cause deleterious effects at the inner surface of a container, such as an increased rate of steel corrosion or degradation of container, thereby potentially reducing waste package integrity.

The alpha particle radiolytic degradation of chlorinated plastics (e.g. PVC) can generate hydrochloric acid. Depending on the design of the waste package, it could be possible for an acid to attack the container wall directly, or more likely, create a chloride solution which could cause degradation of the container surface by chloride induced corrosion mechanisms. Alternatively, a chloride solution could interact with a concrete container causing corrosion of the steel reinforcing. Further information and guidance on container degradation mechanisms is provided by [14].

d) Heat generation

All radioactive wastes generate heat as a result of the energy released during radioactive decay. In addition, chemical processes such as corrosion and microbiological processes occurring within a wasteform may also generate heat. Wigner energy stored within irradiated graphite waste will also be a source of heat if conditions lead to its release.

The DSTS defines a target of 80°C as the maximum temperature for the disposal vaults in the post-backfilling period. Thermal modelling work hasshown that a mean heat output from waste packages of $6Wm^{-3}$ at this time will not cause this target to be exceeded [46]. It has also been shown that individual waste packages with significantly higher heat outputs (i.e. up to ~$100Wm^{-3}$) could be accommodated without the 80°C target being exceeded [47, 48].

In addition to overall GDF temperature issues, the effects of localised heating within individual waste packages and its potential for wasteform damage must be considered. Internal heating of the wasteform will lead to a general increase in rates of reaction (e.g. corrosion) of components of the waste which could potentially lead to differential expansion within the wasteform, excessive generation of gas and/or of particulates. Such effects will be exacerbated by significant localised heating due to, for example, concentrations of activity or reactive chemicals.

A number of potential sources of heat generation exist in ILW, these are described below:

Radioactive decay

The total heat generated by radioactive decay within a wasteform can be calculated directly from the radionuclide inventory and a knowledge of the specific radiogenic heat output from each radionuclide. With typical values of specific heat output of a few W/TBq the heat output of ILW is typically of the order of $1Wm^{-3}$ and, if distributed evenly throughout a wasteform, would not constitute a problem. Some waste streams, however, contain substantially higher concentrations of radionuclides and thus much higher heat outputs. . Concentrations of certain some radionuclides (e.g. plutonium-238) may result in localised heating. RWM have produced guidance on the issues raised by the packaging of sealed sources, which has relevance to other examples of localised concentrations of radionuclides in a wasteform [20].

Corrosion

The heat output from the corrosion of metal wastes, particularly those whose physical form exposes a large surface area to reactants such as water, may be significant and can lead to both general and localised temperature increases in wasteforms. The quantity of heat generated by corrosion can be estimated using the following equation:

$$Q = 3.17 \times 10^{-8} r A \rho \Delta H / M$$

Where: Q is the heat output in watts;
r is the corrosion rate in μm/yr;
A is the corroding area in m^2;
ρ is the density of the metal in kgm^{-3};
ΔH is the heat of reaction in $kJmol^{-1}$; and
M is the atomic weight of the metal.

As the rates of chemical reactions such as corrosion vary with temperature and local chemical/electrochemical conditions, heat output from corrosion will vary similarly. Due account must therefore be taken of the conditions which will be encountered. It should be recognised that heating of a wasteform due to metal corrosion is likely to be accompanied by the creation of corrosion products which may be more friable that the source material, and of greater and of greater volume (see above), this could lead to significant degradation of a wasteform. In practice corrosion reactions should be minimised by selection of an appropriate encapsulant (see Section 7).

Microbiological degradation

It is possible that microbial degradation could generate heat within a wasteform. It should be recognised that heating of a wasteform due to microbial degradation is likely to be accompanied by the generation of gas, which could lead to degradation of a wasteform. In practice microbial degradation should be minimised by selection of an appropriate encapsulation process.

Heat of hydration

The hydration of a cement encapsulant or the curing of a polymer encapsulant may generate large quantities of heat in a relatively short period of time. Consideration should be given to the effect of any exothermic reaction on the long-term properties of the wasteform.

Wigner energy release

Neutron irradiation of graphite within a reactor causes carbon atoms within the graphite lattice to become displaced, resulting in dimensional changes. A large amount of potential energy may be stored within such irradiated graphite and may be released, as Wigner energy, when the graphite experiences particular thermal conditions. The lowest temperature at which a significant release of Wigner energy would occur is considered to be 50°C above the graphite irradiation temperature.

In some cases the irradiation temperature may have been be as low as normal ambient temperatures. Accordingly, significant Wigner energy release could be initiated as a consequence of a fire accident, or even by normal vault temperatures for some wastes.

Depending on the neutron irradiation history and loading of the graphite in a waste package, the effects of Wigner energy release may range from mild heating of the wasteform to significant self-sustaining temperature rise. As a guide, the highest level of Wigner energy recorded to date is approximately 2,700Jg^{-1}which, if this were to be released instantaneously, would result in a temperature rise of up to 1,500°C in irradiated graphite. The possible consequences of such releases under normal and accident conditions should be considered during the development of a packaging proposal for graphite bearing wastes. The potential for such releases within a wasteform may be removed by annealing the graphite at temperatures greater than those experienced during the irradiation prior to waste packaging. Guidance on the packaging of graphite possessing Wigner energy can be found in [49].

How can the effects of wasteform evolution be addressed?

All wasteforms will evolve and their properties will change over the long periods of time involved with the whole process of geological disposal. The emphasis should therefore be on:

i.) Designing the wastform to minimise known evolution processes which have the potential to result in unacceptable changes to the properties of wasteform, and the performance of the waste package; and

ii.) Understanding the processes that will occur in a specific wasteform, their effects on the wasteform and the consequences for waste package performance.

Addressing both of these requirements during the development of a waste packaging process (see Sections 6 and 8) will minimise the potential for wasteform evolution processes to occur.

Following the correct design procedure for a waste packaging process will minimise the potential for wasteform evolution processes to occur. This should include:

- The selection of the optimum waste packaging process by a BAT study will have considered the potential risks posed by wasteform evolution and thereby eliminated unsuitable combinations of waste and encapsulant, and waste container designs.
- The choice of encapsulant through a BAT study will have identified the most suitable wasteform design to minimise the potential for deleterious effects on wasteform performance.
- Development and testing of the formulation envelope will identify the maximum waste loading. It may then be necessary to reduce the waste loading of a formulation to minimise the potential for any degradation mechanisms to occur, and ensure the required wasteform performance.
- If required, the waste container can be designed to ensure that a wasteform degradation mechanism does not affect waste package performance (e.g. the use of steel inner liner and grout annulus to prevent the migration of chloride to the container wall, or the delayed infilling of an annulus void to accommodate any localised expansion of a wasteform).

5.7 Criticality safety

The requirement[23]:

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

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

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

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

For waste packages transported as part of a Type IP transport package, or as a Type IP transport package in their own right, the quantities of fissile material, neutron moderators and reflectors in the waste package should be controlled to ensure that the transport package can be excepted from the requirements of the IAEA Transport Regulations for packages containing fissile material.

How is criticality safety achieved?

The criticality safety of waste packages is not strictly a wasteform issue and is generally controlled by way of limiting the quantity of fissile material, and of other materials of relevance to criticality safety (i.e. neutron moderators and reflectors) in waste packages. This will generally involves the use of a generic, or package specific criticality safety assessment (CSA) to derive a safe fissile mass for the waste package design which will satisfy the criticality safety requirements listed above. Guidance on the control of fissile material in waste packages containing LHGW can be found in [50].

How can the use of anencapsulated wasteform affect criticality safety?

CSA's tend to focus on the ability of fissile material in a waste package to become mobile and to accumulate to form a critical assembly, either within a waste package (during transport or the GDF operational period) or to mix with that from other packages (in the post-closure period following loss of the waste package containment function). The use of an encapsulated wasteform reduces the possibility of the either scenarios occurring, particularly the former.

For packaging proposals where the 47g[24] generic screening level is not exceeded, no specific consideration of the effects of waste conditioning, including whether or not the waste is encapsulated, will be required.

For waste packages containing greater quantities of fissile material, the 'lower screening level' defined by the relevant generic CSAs will apply as these assume such factors as non-uniformly distributed fissile material with optimum water moderation which should pertain for a non-encapsulated wasteform. For waste packages with fissile material inventories of greater than the relevant lower screening level, it should be possible to use the corresponding 'upper screening level' if the waste is encapsulated.

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[23] This requirement comes from the Generic Specification for waste packages containing LHGW [5].

[24] This being the quantity of plutonium-239, or its neutronic equivalent.

6 Guidance on the development of an encapsulation process

This section provides guidance on the development of processes that could be used for the production of encapsulated wasteforms for LHGW.

Once conditioning by processes that include encapsulation has been identified as the optimum approach to the packaging of a particular waste, and the waste package type has been selected, additional functional requirements of the packaging plant can be defined (e.g. required plant footprint and throughput rates). It is then necessary to progress the design of the packaging plant via a number of interdependent development stages which include:

- Definition of the physico-chemical characterisation of the raw waste to be packaged;
- Development of a suitable encapsulant formulation;
- Definition of the wasteform formulation envelope from the packaging plant parameters;
- Wasteform sample testing to demonstrate the long term wasteform properties and behaviour;
- Scale up of the encapsulant formulation and waste packaging process to full scale; and
- Non active and active commissioning of the packaging plant.

It is best practice that packaging plant design is progressed in line with the Disposability Assessment processwhich, as outlined in [10], is applied at each of the key phases in the development of a waste packaging facility. The stages of the Disposability Assessment processcorrespond with the key stages of the development of a waste packaging facility,and the associated safety cases, i.e.:

- *Pre-conceptual assessment*: Provision of advice on packaging options, and other waste management approaches, in advance of the submission of a formal packaging proposal;
- *Conceptual stage*: Initial consideration of the packaging concept and design of the packaging facility;
- *Interim stage*: Technical development of the packaging concept and detailed design of the packaging facility; and
- *Final stage*: Licensing and commissioning of the packaging facility leading to active operations.

6.1 Definition of the formulation envelope

Following the definition of the functional specification for the packaging plant, it is necessary to develop a specific encapsulant formulation and demonstrate that it can be robustly applied to the expected range of process variables, notably the range of physico-chemical properties of the waste, which will occur on the full scale packaging plant. Guidance on the range of encapsulants developed to date by waste producers to condition ILW waste streams is provided in Section 7.

The formulation envelope defines the range over which packaging plant process parameter variables can extend for a particular waste stream, whilst still producing acceptable wasteforms, as defined in Section 4. The efficacy of defined formulation envelope in producing a suitable wasteformis usually assessed at the Interim stage of a disposability assessment.

The retrieval of the waste and its conditioning will have a number of operational variables, including the physico-chemical properties of the wastes before and after any pre-treatment, the acceptable encapsulant formulation waste loadingand the packaging plant process conditions. These variables must be quantified, and the ability of the encapsulant formulation to accommodate the range of variables and produce compliant wasteforms at the extremes of the formulation envelope must be demonstrated.

RWM has produced guidance on the demonstration of robust formulation envelopes for cementitious wasteforms [51] and this is applicable to the range of encapsulant materials that have been proposed for the conditioning of ILW to date, and which have been assessed by RWM(see Section 7).

A packaging plant operating within a defined and robust formulation envelope can be demonstrated to be capable of consistently producing ‘acceptable’(i.e. disposable) waste package products on the basis of:

- Proven quantitative data on the physico-chemical extremes of the retrieved waste, and quantified conditioning process variables;
- Sufficient wasteform development work (e.g. demonstration of acceptable product properties of the wasteform; such as strength development, dimensional stability and gas permeability) based on the wasteforms produced at the extremes of the formulation envelope; and
- Evidence gained during both inactive and active commissioning of the packaging plant.

Operation of the packaging plant to a defined quality management system and plan [52] will provide validation that the waste packages produced over the lifetime of the plant meet the required waste package parameters and quality standards as defined by the WPrS.

Demonstration of the ability of the defined formulation envelope to produce compliant wasteforms is a key component of a submission for anInterim stage disposability assessment and should include the following:

- Quantification (as far as possible) of the proposed packaging plant process parameters that control the formulation envelope; and
- Evidence from the development work that demonstrates the acceptable performance of the wasteforms produced across the full range of the anticipated formulation envelope.

In addition to the guidance provided by [51], extensive work on how to demonstrate encapsulant formulation envelopes, wasteform product properties and the key factors that affect wasteform production and product quality has been carried out by waste producers. A selection of this work is listed below, and information on these is available on request from RWM.

Magnox Ltd has demonstrated robust formulation envelopes for many of ILW waste streams produced by the decommissioning of the Magnox power stations, some specific examples are discussed in Section 7. Figure 7 and 8 show specific examples of demonstrated wasteform envelopes. Magnox has also produced extensive guidance on the development and application of encapsulation processes for the conditioning of ILW waste streams. This guidance includes:

- A summary of the Magnox cement based encapsulants [53];
- Guidance on the methods used for producing and demonstrating encapsulation formulations for the Magnox sludge ILW waste streams [54]; and
- Reports on the required formulation envelope derived from plant tolerances for specific Magnox ILW waste streams [55]

Figure 7 Ternary diagram defining the single point encapsulant formulation for a Magnox pond sludge

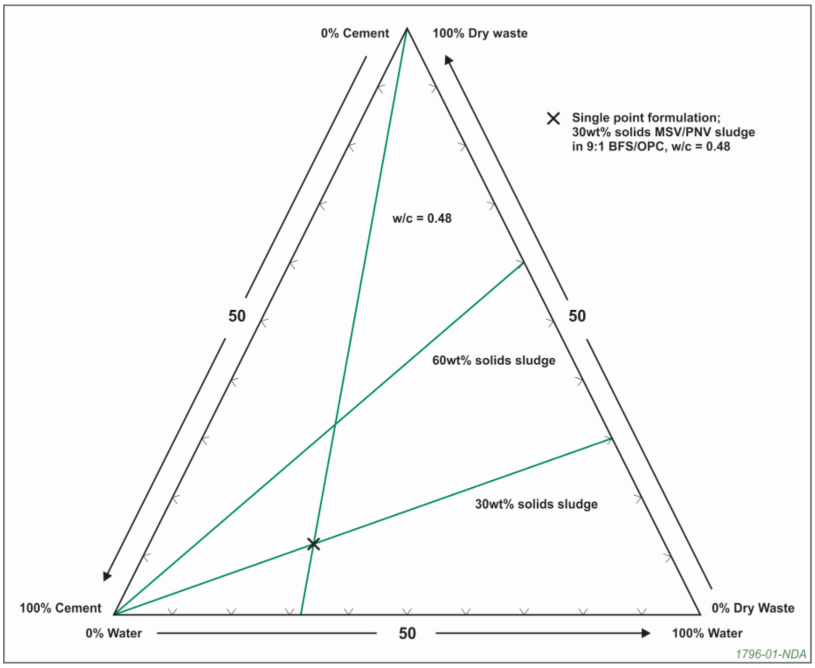
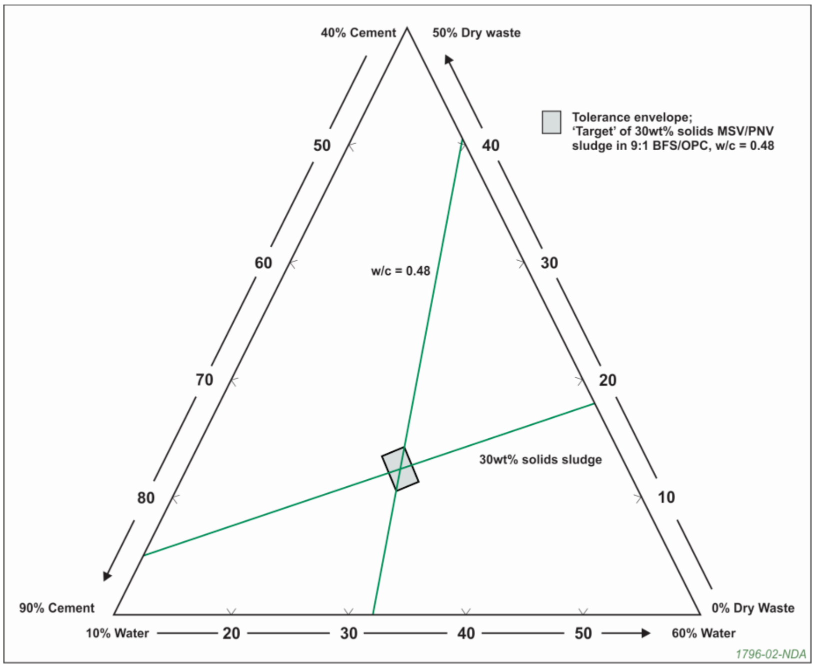
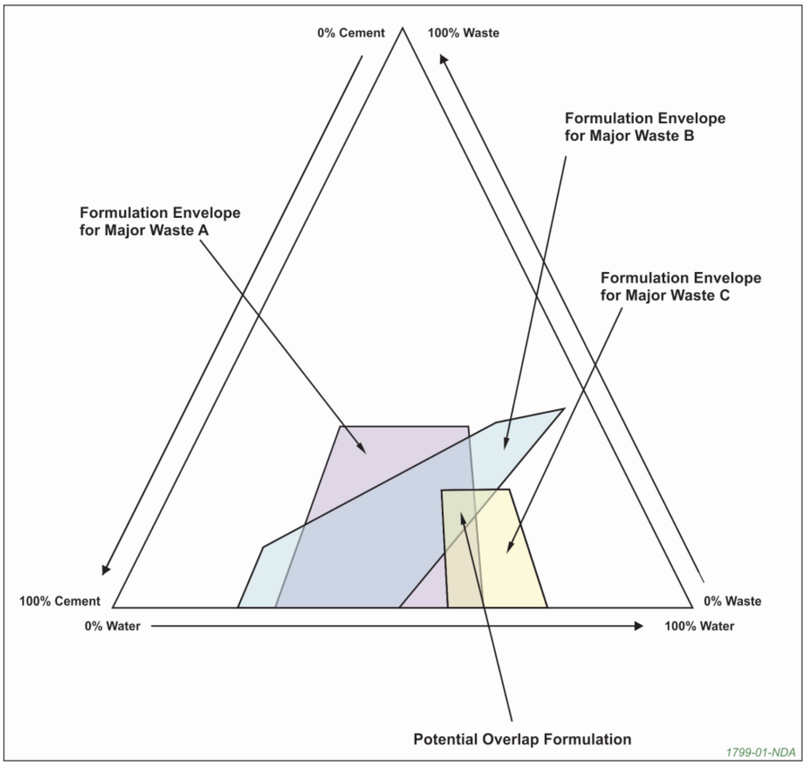


Figure 8 Ternary diagram defining the tolerance envelope for the target encapsulant formulation for a Magnox pond sludge



A methodology for the identification of a suitable cement formulation for a site specific mixed Magnox ILW sludge has been devised (Figure 9), and is reported in [56]. The methodology works by overlapping the ternary diagrams of the cement formulation envelopes determined for the generic Magnox sludges that make up a mixed ILW sludge. The result is a ternary diagram that enables a potentially suitable cement formulation envelope for the mixed sludge to be identified, and a single point waste loading formulation that can be tested using non-active simulant based formulation development work.

Figure 9 Ternary diagram showing how over lapping formulations for different sludge waste streams can be used to define an envelope for a mixed waste system



The findings of [56] showed the methodology to be successful in identifying suitable cement formulations for the three different mixed ILW sludges tested; the selected formulations were shown to have suitable process and wasteform properties by product evaluation testing. The reader is recommended to review this work as the methodology underpins the approach to active sample formulation development advocated by [54].

6.2 The specification and supply of encapsulant materials

The experience of UK ILW packaging plants has shown that the behaviour of cementitious and organic encapsulant materials can vary considerably according to the source and specification of the materials used [53]. It is therefore important that the encapsulant materials used for formulation development should be those that will be used on the full-scale packaging plant. In addition, the security of supply of an encapsulant material should also be considered [22] as part of demonstrating a robust formulation (i.e. the adequate availability of specific encapsulant materials required to package awaste stream for the period over which a packaging plant is expected to operate).

7 Encapsulants assessed to date

RWM hasto date assessed packaging proposals involving a range of wastes encapsulated with different materials. The latter can be classified into two broad groups, inorganic Portland cement (PC) based materials and organic polymer materials. The uses of each of these two groups of encapsulant, together with their benefits and limitations, are discussed below.

7.1 Inorganic Portland cement based encapsulants

The use of PC based encapsulants for the conditioning of a wide range of ILW is a well-establishedapproach. A number of waste producers have carried out extensive cement formulation development programmes that have identified, tested and endorsed by way of the Disposability Assessment processfor the conditioning of operational and decommissioning ILW produced by Magnox power stations [57] and the that arising from spent fuel reprocessing operations at Sellafield and Dounreay.

The cement formulations used to condition ILW typically consist of a pulverised fly ash (PFA) pozzolanic material or latent hydraulic ground granulated blast furnace slag (GGBS), activated using a hydraulic PC (normally Cem1 PC[25]). Blended materials are used to reduce heat production and overcome the retardation of cement hydration by inorganic and organic waste components. The use of PFA and GGBS can also improve chemical durability, restrict penetration by chloride ions and increase the strength and stability of a wasteform compared with the use of a purePC encapsulant.

Although PFA and GGBS/PC based formulations have been found to be suitable to encapsulate the majority of ILW waste streams to date, more specialised cement powders and pozzolana have also been used to produce bespoke cement formulations to condition a small number of waste streams.

The use of PC based encapsulants have been endorsed for the conditioning of a wide range of waste streams; examples are reported below.

- GGBS/Cem1 formulations have been endorsed for conditioning a range of sludge, resin and metal wastes including the following:
  - Magnox swarf at Sellafield [58, 59];
  - Solid ILW (Magnox fuel element debris and graphite sleeves) at Hunterston [60]; and
  - Sludge and resin ILW waste streams at Hunterston [61].
- PFA/Cem1 PC formulations are used to encapsulate a range of liquid and solid wastes:
  - Solid ILW (Magnox fuel element debris and graphite sleeves) at Hunterston [60]; and
  - Raffinates produced during the reprocessing of fast reactor fuel at Dounreay [62].

Further guidance on PC encapsulant materials, specific formulations and their applications are provided in [22] and [53].

Whilst PC based encapsulants have been proven to be versatile in the conditioning of ILW there are specific waste streams that are unsuited to conditioning using such encapsulants.

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[25] http://www.hanson.co.uk/sites/default/files/assets/document/hanson-cem-1-portland-cement-data-sheet.pdf

For example, the high pH porewater of GGBS or PFA/PC encapsulants are known to readily react with Magnox and aluminium cladding and uranium metal fuel, producing heat, hydrogen gas, and the [possibility for wasteform damage from expansive corrosion [63]. Corrosion of reactive metals in an alkaline cement matrix initially results in an acute phase of gas production, followed by chronic gas production at a reduced rate over the long-term storage period. Development of an expansive mineral phase on reactive metal surfaces can also cause degradation of the wasteform by cracking. When uranium reacts with hydrogen in a reducing environment, uranium hydride may be formed, which under some circumstances can be pyrophoric. The most effective ways of minimising the reactive metal corrosion reactions are by reducing the pH and water content of an encapsulant [63]; this is commonly achieved by the use of organic or geopolymer encapsulants.

Other wastes that have been found to be incompatible with PC based formulations are chloride and sulphate bearing wastes, and wastes that are difficult to infiltrate, such as filters (but see [16]).

7.2 Organic polymer encapsulants

For some ILW waste streams, such as those containing reactive metals or high concentrations of specific chemical species (e.g. sulphate or soluble chloride salts), the use of organic polymer encapsulants has been shown to produce acceptable wasteforms, with improved performance compared to the use of PC based encapsulants.

A suitably chosen organic polymer encapsulant can achieve the following [64]:

- Minimise the potential for deleterious reactions between the encapsulant matrix and the ILW occurring, and thereby provide the required long-term wasteform stability;
- Provide a low gas and water permeability matrix, restricting the release of radioactive gases such as radon and giving low leach rates for radionuclides; and
- Allow a higher waste loading to be achieved compared to the use of PC based encapsulants.

A number of organic polymer encapsulants have been endorsed for the conditioning of UK ILW waste streams. Vinyl ester styrene (VES) has been used to package the following:

- Windscale Pile fuel and isotope waste[26];
- Lewatit and AW500 ion exchange materials at Trawsfynydd [65]; and
- Radium wastes at Harwell using the vinyl ester resin in-situ polymer (a type of VES) [66].

An epoxy resin encapsulant manufactured by Alchemie has been developed as an alternative to the VES polymer system. The use of such epoxy resin encapsulants has been endorsed for the packaging of:

- Radium bearing wastes [66]; and
- Uranium metal fuel from GLEEP[27] [67].

Compared with PC based encapsulants, organic polymer encapsulants have the disadvantage of being a low pH chemical barrier and having relatively modest thermal stability and radiation resistance. However, these properties do not prevent the use of organic polymers as encapsulants. It should also be noted that organic polymer

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[26] The use of vinyl ester resin in-situ polymer was endorsed as the encapsulant for the Windscale Pile fuel and isotope waste. It is expected that the Alchemie epoxy resin encapsulant will be proposed for use as part of a future Interim stage submission.

[27] Graphite Low Energy Experimental Pile, a reactor that was sited at Harwell.

encapsulants are generally more expensive than cement based systems and this is can be factor which limits their use.

Recent work has investigated the long-term impacts of polymer-encapsulated wastes on the components of the disposal system, and the implications for GDF long-term safety. The study found that co-location of polymer-encapsulated ILW with cement-encapsulated ILW would be feasible under certain circumstances [64].

8 Demonstration of the properties of an encapsulated wasteform

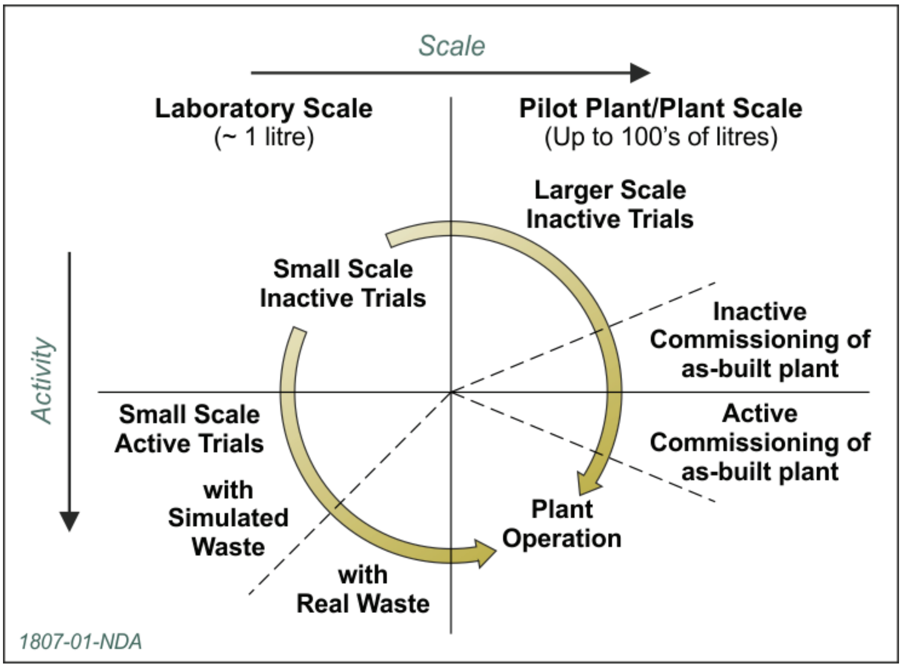
The requirements for the properties of all types of wasteform are the same, irrespective of whether they involve encapsulation of not. An encapsulated wasteform however is likely to make a greater contribution to the safety functions of a waste package by way of its principal function; the containment of radionuclides and other hazardous materials in the waste package during transport and the GDF operational period. The dimensional stability of such a wasteform also contributes to the ability of a waste package to withstand compressive loads and, in some circumstances;it may contribute to criticality safety and ensure that radionuclides are released at a limited rate once the waste container is penetrated by groundwater [14].

8.1 Wasteform trials

Typically, the properties of a manufactured wasteform will be determined by the use of small and large scale trials designed to provide specific empirical evidence; the aim of such trials should be to demonstrate the properties of the wasteforms produced at the formulation envelope extremes (Section 6.1, [51]). Where possible, pre-existing data produced by previous testing of analogous wasteforms should be reported by Conceptual and Interim stage submissions for disposability assessment, so as to minimise the safety and cost implications of new work.

Figure 10 illustrates two possible approaches to the development of a wasteform formulation by grouped the different types of wasteform trials into four categories, each of which has a distinct role to play in providing information to support the different stages of submissions for disposability assessment [51]. Information obtained at earlier trial stages (i.e. small scale/non-active) may be sufficient to give confidence in the final product, especially if supported by evidence from the packaging of similar wastes using similar packaging processes. This may justify the omission of some or all subsequent trial stages. Any requirement for additional specific experimental work can then be identified during the disposability assessment.

Figure 10 Categories and progression of wasteform trials



The design of a wasteform trial needs to pay careful consideration particularly to how non-active simulant waste and active waste samples are used to evaluate encapsulant and wasteform performance. Non-active trials should utilise simulants that are designed to match the physico-chemical properties of the waste stream envelope as closely as possible. In demonstrating the robustness of a formulation envelope, the nature of the waste simulants should be reported [51, 54, 68] (see Section 6.2 for guidance on the use of specific encapsulant materials for wasteform trials.)

The appropriateness of non-active simulants as analogues of an ILW waste stream can be confirmed through active trials. However, it should be recognised that there is a potential risk that a simulant waste or active waste sample may not be fully representative of the retrieved waste that will be packaged by a packaging plant. Further guidance on the design of wasteform trials is given by [54].

Wasteform demonstration trials can be progressed by one or both of the two routes shown in Figure 10:

- From small-scale non-active trials to larger-scale (i.e. up to full waste package size) trials during non-active commissioning of the packaging plant; and/or
- From small-scale non-active trials to small-scale active trials, to confirmatory trials during active commissioning of the packaging plant.

The scale at which an encapsulant and wasteform is prepared can have significant effects on some wasteform properties. Examples of wasteform properties that may show significant change as a function of scale-up are mixability of the pre-set product, the hydration exotherm and related parameters such as setting time and early-age strength development, bleed water volume, and dimensional stability of the cured wasteform. If wasteform development work utilises plant other than that which will be used for actual waste packaging, then the possible effects on the wasteform products should be clearly understood.

8.2 Demonstration of wasteform properties

The extent of any applicable restrictions on target wasteform properties is dependent on the physico-chemical properties of the waste to be packaged and the design of the waste packaging process. In general, the use of an appropriately developed encapsulant formulation combined with a mixing/curing process will produce a homogeneous and monolithic wasteform, with the absence of free liquids, activity in fine particulate form, voidage and heterogeneity. Likewise a proposal to produce a wasteform by the infilling of solid waste should ensure that necessary measures such as internal furniture are used to ensure acceptable distribution of activity within a waste package.

The presence of toxic, reactive or hazardous materials in a waste stream will be identified by a waste packager and reported in the submitted waste stream inventory. The measures to be taken to ensure that such materials are controlled and excluded from the waste packaging process will be defined in the WPrS.

8.3 Test methods and key wasteform parameter data

The key experimental procedures and specific tests used to define a cement encapsulant wasteform product parameters are reported in this section. A revised experimental procedure and performance requirements may be required for wasteforms comprising organic polymer encapsulants.

8.3.1 Test methods for pre-set Portland cement based wasteforms

Bleed: Bleed is determined by measuring the volume of overstanding water removed from the surface of a small scale sample (100ml) after 24 hours curing. Results are expressed as a percentage of the total volume of the sample (solid and bleed).

Set: Set is determined using the Vicat technique [69]. Set is defined by zero penetration of the cement sample by a weighted needle. Testing can be determined manually on a small scale sample (100ml) or by an automated machine using a 300ml sample.

Viscosity: Viscosity can be measured using small sample volume 75ml with a proprietary viscometer.

8.3.2 Wasteform product evaluation test methods

The following product evaluation tests have been used to determine the wasteform properties of simulated Magnox sludge wasteforms [54].

Sample preparation: Grout is poured into standard moulds (100mm cubes, 286mm x 26mm x 26mm prisms and 500mm x 100mm x 100mm beams) and vibrated, according to British Standard procedures [70]. The samples are then covered with polythene and left to cure for 48 hours in a controlled environment (see below). After hardening (1 to 2 days) the samples are removed from the mould, sealed in polythene bags, to limit desiccation during storage, and returned to the controlled temperature/humidity environment.

Sample storage: The sample storage environment is important as fluctuations in temperature and humidity can significantly affect wasteform behaviour. Storage environment is considered a key factor controlling the chemical and physical evolution of a wasteform. Cementitious samples should be stored at temperatures of between 18 and 22°C and a relative humidity of greater than 90%.

*Compressive strength:*Compressive strength is measured using standard 100mm cubes, which are loaded progressively until failure occurs [71].

Elastic modulus and strength: Measurements of the propagation of pulsed ultrasound through cement samples can be used to determine a number of properties including uniformity, the presence of voids, cracks and other imperfections, elastic modulus and strength, without destroying the sample [72]. The ‘impulse excitation technique’, in which an object is subjected to a small mechanical impulse, (e.g. [73]), is a very simple, quick and reliable means of determining the dynamic modulus of elasticity of cement samples. The test is non-destructive and gives valuable information related to elasticity and the development of sample strength, and hence product quality.

Density: The density of 100mm cubes is calculated from weight difference when weighed in air and water [74].

Dimensional stability: Dimensional stability is determined using prisms (26mm x 26mm x 286mm) by measuring the change in length per unit length with time [75].

9 Summary

For many types of LHGW the most appropriate approach to their conditioning for geological disposal involves intimate encapsulation of the waste in a matrix of a cementitious or polymeric material.

The encapsulation of waste can take a number of forms and the wasteforms that would result from these can be divided into four broad types, each of which has been shown to be capable of producing wasteforms, and waste packages, with the necessary properties for geological disposal:

i.) backfilling of loose heterogeneous waste with a suitable grouting medium;

ii.) in-drum mixing of a homogeneous waste with a suitable encapsulant;

iii.) external mixing of the waste and encapsulant and pouring into a waste container; and

iv.) enclosing waste within a grout annulus.

The assessment of an encapsulated wasteform, and of its ability to make the required contribution to the overall performance of the waste package, will take into account the influence of such a wasteform to provide adequate:

- Physical immobilisation of radionuclides;
- Mechanical and physical properties;
- Chemical containment of radionuclides;
- Control of hazardous materials;
- Control and management of gas generation;
- Criticality safety; and
- Consequences of wasteform evolution.

RWM has to date assessed several packaging proposals involving the use of inorganic cements and organic polymers for the encapsulation of ILW with a wide range of physico-chemical properties. The choice of whether to use an inorganic cement or an organic polymer encapsulant will depend on a number of parameters. The use of cement based encapsulants for the conditioning of a wide range of ILW is a well-established approach. Extensive wasteform development work has been carried out to identify suitable cements for a wide range of wastes, leading to conditioning processes that have been endorsed by the Disposability Assessment process. This has included the use of specialised cement powders and pozzolana to produce bespoke formulations for challenging waste types.

For some ILW waste streams, such as those containing reactive metals or high concentrations of chemical species such as sulphate and/or chloride ions, acceptable wasteforms can be produced using organic polymer encapsulants. A suitably chosen polymer encapsulant can minimise the potential for deleterious reactions between the wastes encapsulant matrix and thereby provide long-term wasteform stability as well as other benefits such as providing a low permeability matrix and allowing higher waste loading when compared to those achieved by cement based systems.

It should be noted that not all wastes are suitable for encapsulation and that for some, non-encapsulation may offer benefits. Reference should be made to the counterpart of this guidance which deals with the production of such wasteforms (i.e. [7]).

References

1 Department of Energy and Climate Change, *Implementing Geological Disposal, A Framework for the long-term management of higher activity radioactive waste*, URN 14D/235, 2014.

2 NDA, *Geological Disposal: Generic Waste Package Specification,* NDA Report No. NDA/RWMD/067, 2012.

3 NDA, *Geological Disposal: Introduction to the RWM Waste Package Specification and Guidance Documentation*, WPS/100/04, 2015.

4 NDA, *Geological Disposal: Generic Disposal System Technical Specification*, NDA Report No. NDA/RWMD/044, 2010.

5 NDA, *Geological Disposal: Generic Specification for waste packages containing low heat generating waste*, NDA Report No. NDA/RWMD/068, 2012.

6 NDA, *Geological Disposal: Wasteform Specification for waste packages containing low heat generating waste,* WPS/501, 2012.

7 NDA, *Geological Disposal: Guidance on the production ofnon-encapsulated wasteforms,* WPS/503, 2015.

8 NDA, *Geological Disposal: Guidance on the application of the Waste Package Specifications for unshielded waste packages*, WPS/701, 2014.

9 NDA, *Geological Disposal: Guidance on the application of the Waste Package Specifications for shielded waste packages*, WPS/702, 2014.

10 NDA, *Geological Disposal: An Overview of the RWM Disposability Assessment Process, WPS/650/03, 2014.*

11 HSE/EA/SEPA, *The management of higher activity radioactive waste on nuclear licensed sites. Joint guidance from the Health and Safety Executive, the Environment Agency and the Scottish Environment Protection Agency to nuclear licensees*, 2010.

12 NDA, *Geological Disposal: The Safety of a Geological Disposal System: An Overview,* NDA Report No. NDA/RWMD/010, 2010.

13 NDA, *Geological Disposal: Guidance on the preparation of submissions for the disposability assessment of waste packages*, WPS/908/03, 2014.

14 NDA, *Geological Disposal: Package Evolution Status Report,* NDA Report No. NDA/RWMD/031, 2010.

15 NDA, *Geological Disposal: Guidance on the issues arising from the packaging of non-encapsulated wastes WPS/914,* February 2009.

16 Nirex, *Guidance note on the packaging of filters*, WPS/905, 2006.

17 Environment Agency, *Principles of optimisation in the management and disposal of radioactive waste,* April 2010.

18 Nuclear Industry Safety Directors Forum, *Best Available Techniques (BAT) for the Management of the Generation and Disposal of Radioactive Wastes. A Nuclear Industry Code ofPractice,* Issue 1, December 2010.

19 NDA, *Guidance on the packaging of radon generating wastes*, WPS/902/02, 2015.

20 NDA, *Guidance note on the packaging of closed sources*, WPS/906, 2009.

21 NDA, *Guidance note on the packaging of tritium bearing wastes*, WPS/907, 2007.

22 Nuclear Technologies plc, *The Security of Supply of Strategic Materials for ILW Packaging,* NTL Report NT/722500264/R320 Issue 2, 2009.

23 NDA, *Geological Disposal: Waste Package Specification for 500 litre drum waste packages,* WPS/300/03, 2013.

24 NDA, *Geological Disposal: Generic Post Closure Safety Assessment,*NDA Report No. NDA/RWMD/030, 2010.

25 British Standards Institution, *Guide to the Preparation of Specifications*. BS7373:1998.

26 Nirex, *Guidance on the Immobilisation of Radionuclides in Wasteforms*, WPS/903, 2005.

27 IAEA, *Regulations for the Safe Transport of Radioactive Material*, 2012 Edition, Specific Safety Requirements No. SSR-6, 2012.

28 HSE, *Nuclear Installations Inspectorate: Safety Assessment Principles for Nuclear Facilities, 2006 Edition*, Revision 1, 2006.

29 NDA, *Geological Disposal:Generic Operational Safety Case main report*, NDA Report No. NDA/RWMD/020, 2010.

30 NDA, *Geological Disposal: Generic Disposal Facility Designs*, NDA Report No. NDA/RWMD/048, 2010.

31 NDA, *Geological Disposal: UILW Waste Package Impact Accident Conditions*, NDA Technical Note No. 18835729, 2013.

32 RWMD, *Geological Disposal Facility Design: Handling and emplacement operations for ductile cast iron containers*, RWMD Technical Note No. 16168769, 2012.

33 NDA, *Geological Disposal: Guidance on the use of grout caps in waste packages,* WPS/915, 2009.

34 NDA, *Geological Disposal: Waste package accident performance status report*, NDA Report No. NDA/RWMD/032, 2010

35 NDA, *Geological Disposal: UILW waste package fire accident conditions*, NDA Technical Note No. 18836828, 2013.

36 NDA, *Geological Disposal: Guidance on the sealing and venting of waste packages* WPS/920, 2013.

37 IAEA, *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material,* Safety Guide No. TS-G-1.1 (ST-2), 2002.

38 R David Lide, *Handbook of Chemistry and Physics*, 77th Edition, 1996-1997.

39 Electrowatt-Ekono, *Calculation of Effective Thermal Conductivity for the Grouted ILW Matrix in a Repository Vault*, EWE-2916/001, 2001.

40 Nirex, *Topical Report on the Thermal Analysis of an ILW Repository*, Nirex Report N/086, 2003.

41 CornwellK, *The Flow of Heat*. Published by the NVR Company, 1977.

42 British Standards Institution, *Methods for Determining Thermal InsulatingProperties,* BS 874:1973.

43 NDA, *Guidance on the use of organic polymers for the packaging of low heat generating waste, WPS/901/02, 2015.*

44 NDA, *Geological Disposal: Guidance on the control of NAPLs and their precursors during the packaging of LHGW*, WPS/924, 2015.

45 NDA, *Geological Disposal: Gas status report,* NDA Report No. NDA/RWMD/037, December 2010.

46 Electrowatt-Ekono, *Thermal Analysis of 7 by 7 Stillage Arrays in ILW Vaults*, EWE-17314/002, Revision 4, 2001.

47 AEA Technology, *Waste Package Temperature Modelling in Support of the Development of an Improved System for Recording Waste Package Radionuclide Inventory and Related Data*, TEPT 2620 TS 09 - TN 1, 1998.

48 Serco, *3D Thermal Modelling of Waste Packages in Backfilled Vaults*, SERCO/TAS/2584/W1 Issue 1, 2008.

49 Nirex, *Issues to Address For Endorsement of Proposals for Packaging Wastes Containing Graphite with Wigner Energy*, Nirex Report No. N/058, 2002.

50 NDA, *Geological Disposal: Guidance on the control of fissile material in waste packages,* WPS/916, 2013.

51 NDA, *Guidance on the Characteristics and Demonstration of Robust Formulation Envelopes for Cementitious Wasteforms*, WPS/904, 2007.

52 NDA, *Waste Package Quality Management Specification: Guidance material,* WPS/210/02, 2008.

53 AEA Technology, *Summary report -process and product properties of reference encapsulants,* WMT(03)P071, 2006.

54 Nuclear Technologies plc, *Assessment of the Use of Active Sludge for Cementation Trials,* NTL Report 722500135/R319, Issue 1, 2008.

55 AEA Technology, *Review of the effect of anticipated waste retrieval and packaging plant tolerances on cemented wasteform product quality - Part 1* AEAT/R/NT/0275 Issue 2, 2003.

56 AEA Technology, *Methodology for specifyingformulations for the solidification of mixtures of wastes-Part 3,* AEAT-2770 Issue1,1997.

57 Streatfield R E, *A review and update of the BNFL cement formulation development programme for the immobilisation of intermediate level wastes from Magnox power station,* WM'01 Conference, Tucson AZ, 2001.

58 NDA, *Periodic Review of Letters of Compliance for Packages Manufactured at Sellafield Magnox Packaging plant (Post-Final stage), Summary of Assessment Report*, 2010.

59 NDA, *Packaging of Wastes from the Magnox Swarf Storage Silos at the Silos Direct Packaging plant (Interim stage). Summary of Assessment Report*, 2008.

60 NDA, *Solid ILW at Hunterston Magnox Decommissioning Site (Interim Stage) Summary of Assessment Report*, 2010.

61 NDA, *Sludge and resin waste at Hunterston A in 3m^3 drums (Interim Stage) Summary of Assessment Report*, 2010.

62 NDA, *DFR Raffinate at the Dounreay (Interim Stage), Summary of Assessment Report*, 2008.

63 NNL, *The effect of encapsulant type and trial methodology upon the rate of hydrogen evolution from metallic uranium- Interim progress report 3,* NNL(09) 10141, Issue 1, 2009.

64 Serco, *Consideration of Polymer-Encapsulated ILW in a Geological Disposal Facility,* Serco/TS/003866/02 Issue 01, 2010.

65 Nuclear Technologies plc, *The security of supply of strategic materials for ILW packaging,* NTL Report 722500264/R320/Issue 2, 2009.

66 NDA, *Assessment of modifications to pre-treatment and packing of remaining radium wastes, Summary of Assessment Report*, 2012.

67 NDA, *Encapsulation of GLEEP fuel at Harwell, (Final stage), Summary of Assessment Report*, 2011.

68 Lee DJ and Fenton A,*The development of cement formulations for radioactive waste encapsulation, in Stabilisation and solidification of Hazardous, radioactive and mixed wastes, 2nd* volume, ASTM STP 1123, Gillam TM and Wiles CC, p348-358.

69 *American Society for Testing and Materials Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle*, ASTM C191, 1982.

70 British Standard Specification BS1881, 1983.

71 British Standard, *Testing Concrete, Specification for Compressive Testing Machines for Concrete*, BS 1881, Part 115, 1983.

72 British Standard Specification BS4408: Part 5:1974.

73 http://grindosonic.com/en/products/prod1.htm

74 British Standard*, Testing Concrete, Method for Determination of Density of Hardened Concrete,* BS 1881, Part 114, 1983.

75 American Society for Testing and Materials, *Standard Practice for theDetermination of Length Change of Hardened Cement Paste, Mortar and Concrete*, ASTM C490-89, 1983.

Glossary of terms used in this document

activity

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

The IAEA Transport Regulations define a unit of activity, the A_2, as a means of standardising the dose consequences of different radionuclides on the basis of the different possible exposure pathways that could occur following the release of radionuclides from a transport package. A_2 values (in TBq) for a wide range of radionuclides are listed in Table 2 of the IAEA Transport Regulations [27].

alpha activity

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

backfill

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

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

backfilling

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

barrier

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

beta activity

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

buffer

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

conditioning

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

container

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

containment

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

criticality

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

criticality safety

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

disposability

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

disposability assessment

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

disposal

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

disposal facility (for solid radioactive waste)

An engineered facility for the disposal of solid radioactive wastes.

disposal system

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

disposal vault

Underground opening where ILW or LLW waste packages are emplaced.

dose

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

dose rate

The effective dose equivalent per unit time. Typical units of effective dose are sievert/hour (Svh^{-1}), millisieverts/hour ($mSvh^{-1}$) and sievert/year (Svy^{-1}).

emplacement (of waste in a disposal facility)

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

Environment Agency (EA)

The environmental regulator for England and Wales. The Agency's role is the enforcement of specified laws and regulations aimed at protecting the environment, in the context of sustainable development, predominantly by authorising and controlling radioactive discharges and waste disposal to air, water (surface water, groundwater) and land. The Environment Agency also regulates nuclear sites under the Environmental Permitting Regulations and issues consents for non-radioactive discharges.

environmental safety case

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

fissile material

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

geological disposal

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

geological disposal facility (GDF)

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

half-life

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

hazardous materials

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

Health and Safety Executive (HSE)

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

higher activity radioactive waste

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

immobilisation

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

Industrial Package (Type-IP)

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

intermediate level waste (ILW)

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

International Atomic Energy Agency (IAEA)

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

Letter of Compliance (LoC)

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

low heat generating waste (LHGW)

A broad category of waste which includes ILW and other wastes with similar radiological properties.

low level waste (LLW)

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

low specific activity (LSA) material

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

Nirex (United Kingdom Nirex Limited)

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

Nuclear Decommissioning Authority (NDA)

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

Office for Nuclear Regulation (ONR)

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

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

operational period (of a disposal facility)

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

passive safety

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

plutonium (Pu)

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

post-closure period (of a disposal facility)

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

radioactive decay

The process by which radioactive material loses activity naturally.

radioactive material

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

radioactive waste

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

Radioactive Waste Management Ltd (RWM)

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

radioactivity

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

radionuclide

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

safety case

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

safety function

A specific purpose that must be accomplished for safety.

shielded waste package

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

shielding

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

stack (of waste packages)

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

transport package

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

Transport Regulations

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

transport system

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

unshielded waste package

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

uranium (U)

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

waste acceptance criteria (WAC)

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

waste container

Any vessel used to contain a wasteform for disposal.

wasteform

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

waste package

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

waste packager

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

Certificate No LRQ 4008580

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