Radioactive Waste
Management

WPSGD no. WPS/503/01

Geological Disposal

Guidance on the production of non-encapsulated wasteforms

August 2015

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

Executive Summary

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

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

This document provides guidance 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 does not involve encapsulating. 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/503 - VERSION HISTORY		
VERSION	**DATE**	**COMMENTS**
WPS/503/01	August 2015	Aligns with Generic Specification for waste packages containing low heat generating waste (NDA Report No. NDA/RWM/068) as published August 2012. Produced, along with WPS/502 (Guidance on 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 technology
DSSC	Disposal System Safety Case
DSTS	Disposal System Technical Specification
EBS	engineered barrier system
ESC	Environmental Safety Case
GDF	geological disposal facility
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
LSA	low specific activity
MRWS	Managing Radioactive Waste Safely
NAPL	non-aqueous phase liquid
NDA	Nuclear Decommissioning Authority
PVC	poly vinyl chloride
RWM	Radioactive Waste Management Ltd
WAC	waste acceptance criteria
WPS	Waste Package 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 (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 the waste container without further conditioning.

This document provides guidance on the means by which non-encapsulated wasteforms with the required properties can be produced. A counterpart dealing with the production of 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 non-encapsulation of wastes, identifies the types of LHGW 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 for LHGW (i.e. [6]) and discusses their application to non-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 non-encapsulated wasteforms.
- Section 6 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 a non-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 inthe 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 process also 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[1] predicted to arise in the UK. However, it is

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[1] 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 GWPSidentifiesthe 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[2] to workers and members of the public;
    - Preclude criticality;

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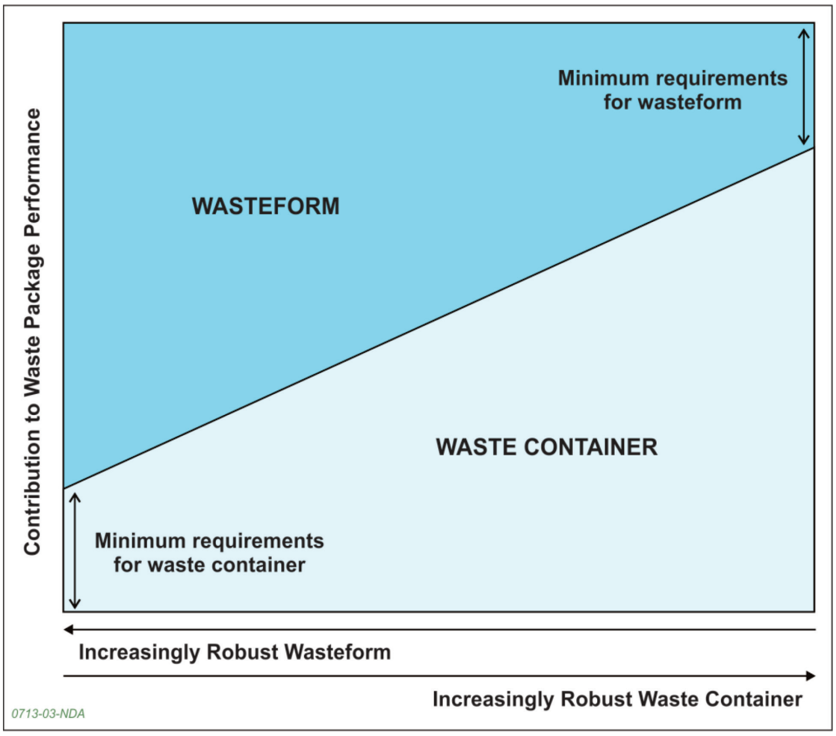
[2] In this context radiation dose is that which could result from exposure to direct radiation from the surface of the waste package.

  - 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[3] 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, wastecontainers 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.

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

3 The use of non-encapsulated wasteforms in the packaging of LHGW

3.1 The definition of a non-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.'*

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. However it is acknowledged that whilst such an approach can produce wasteforms which satisfy all of the requirements of safe geological disposal, it is by no means the only manner by which every type of waste can be conditioned.

The description 'non-encapsulated wasteform' covers a wide range of wasteforms, which can extend from waste that has received little or no treatment prior to packaging, to that which has been 'entombed' but without intimate mixing of the waste with an encapsulating medium.

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 the intimate mixing of a waste with a suitable material, and is a possible means of achieving immobilisation.

The means by which adequate immobilisation is achieved in a 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. Some wastes, such as those that arise from the decommissioning of nuclear reactors, may contain only radionuclides which are the result of neutron irradiation. Such radionuclides, which include carbon-14 in irradiated graphite and cobalt-60 in irradiated steel, exist within the atomic structure of the waste and are effectively immobile. For other wastes the radionuclides may be present in the form of surface contamination and associated with small particles which can become detached from the bulk of the waste. These, and other radionuclides which are gaseous (e.g. tritium), or which may chemically bind with other materials to form gases (e.g. carbon-14) are intrinsically mobile whereas those which readily dissolve in water (e.g. isotopes of caesium and strontium) are considered to be relatively mobile.

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.'*

As stated above this guidance is aimed at wasteforms where intimate encapsulation is not the approach selected to ensure the adequate immobilisation of radionuclides and other hazardous materials within a wasteform. Where encapsulation is the chosen approach, the counterpart to this guidance should be used (i.e. [7]).

3.2 Waste types potentially suitable for non-encapsulation

In order for a waste to be deemed suitable for a conditioning process that would result in the creation of a non-encapsulated wasteform there are a number of basic criteria that will have to be satisfied [15]. At the highest level a waste package containing a non-encapsulated wasteform must be capable of satisfying the necessary requirements of the relevant packaging specification. This will include the providing 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.

Whilst the absence of any process aimed at intimately encapsulating the waste will not affect the manner in which a disposability assessment is carried out, it will mean that certain aspects of waste package performance will receive greater attention than in the case of a proposal which includes encapsulation of the waste. The nature of the waste container, and the extent of its role in achieving satisfactory waste package performance, will be considered in the evaluation of the properties and performance of the proposed waste packages, informed by information generated during the evaluations of waste container design and integrity, and of the wasteform itself. The latter will also include an evaluation of the expected evolutionary processes of the waste container and the wasteform. It should be noted that, as illustrated in Figure 1, the wasteform will always play some role and, as a consequence, very few waste types will be suitable for packaging without some, albeit possibly only resulting from limited, conditioning. Irrespective of the nature of the wasteform (i.e. encapsulated or non-encapsulated) the wasteform requirements defined by the packaging specifications are not absolute and it is the role of the Disposability Assessment process to consider whether the proposed conditioning process(es) will result in a wasteform that will adequately contribute to overall waste package performance.

If encapsulation is not to be part of a conditioning process the waste will be required to have a number of characteristics which will make it more likely capable of satisfying the requirements specified for the wasteform by the relevant packaging specification. In summary, such wastes should be:

- Bulk non-friable solids without significant fine particulate material;
- Relatively free of non-fixed surface contamination, or capable of easy decontamination;
- Dry, or such that any free liquid can be easily removed;
- Of sufficient compressive strength so that it is not readily fractured when subjected to the loads that would be expected under normal and accident conditions during transport or disposal;
- Resistant to atmospheric corrosion; and
- Chemically inert (i.e. not combustible, pyrophoric or exhibit reactive or exothermic behaviour), and chemically compatible with the proposed waste container material.

From these basic characteristics a number of generic waste types can be identified which may potentially be suitable for non-encapsulation, these are listed in Table 1.

The list is not exhaustive and serves to provide examples of the wastes types which are potentially suitable for non-encapsulation. For example, it may be possible to show that some polymeric materials are suitable for non-encapsulation, provided it can be shown that potential issues associated with fire and impact accidents and the production of breakdown products from radiolysis and other processes (e.g. putrescence) are not significant to waste package performance.

Table 1 Waste types with potential for non-encapsulation

Typical waste types		Desirable characteristic of waste					
		Lack of particulate	Low surface contamination	Dry	Strength	Corrosion resistant	Inert
Stainless steel	Chemical plant pipe work	✓	(✓)	✓	✓	✓	✓
	Irradiated reactor components	✓	✓	✓	✓	✓	✓
Other metals (aluminium, lead etc.)		✓	✓	✓	✓	(✓)	✓
Building rubble (concrete etc.)		×	×	✓	×	✓	✓
Glass and ceramics		✓	✓	✓	×	✓	✓
Graphite	AGR sleeves	×	✓	✓	×	✓	✓
	Reactor core	✓	✓	✓	✓	✓	✓

Key: ✓ Waste types which would normally be expected to possess the required characteristic.

(✓) Waste types which would possess the required characteristic in some cases.

× Waste types which would generally not be expected to possess the required characteristic.

It should be noted that there are some wastes where the use of an intimate encapsulant can have a deleterious effect on the properties of a waste, and its ability to immobilise radionuclides. These include notably neutron irradiated materials (e.g. notably steels) and metals into which tritium has diffused and the radionuclides associated with such wastes are effectively immobile. This property could be lost if chemical reactions between an encapsulating medium and the waste resulted in damage to the waste and the release of previously immobile radionuclides under normal and/or accident conditions. For such wastes non-encapsulation could be the *preferred* approach to conditioning.

3.3 Selection of the waste container for use with a non-encapsulated wasteform

In principle, any of the three waste container types identified in Section 2.3 would be suitable for use with a non-encapsulated wasteform. However, the suitability of a specific design of waste container for use with a non-encapsulated wasteform will depend to a large degree on the physical and chemical nature of the waste.

Waste packages containing non-encapsulated wasteforms call use either thin walled waste containers, to create unshielded or shielded waste packages, or thick-walled containers to create robust shielded waste packages. In Section 2.2 the relative contributions of the waste container and the wasteform to the achievement of the required performance of the waste package was discussed. This would suggest that a non-encapsulated wasteform would always need to be used in conjunction with a more robust waste container. However, as discussed above there are a number of waste types for which packaging without encapsulation and using a thin-walled stainless steel waste container would result in waste packages with the necessary properties for transport and disposal.

a) Use of an unshielded or shielded waste container

A waste stream with demonstrably suitable physico-chemical properties, which would be expected to be maintained over a suitable timescale, could be packaged as a non-encapsulated wasteform in either an unshielded or a shielded waste container. Such an approach would be suitable for bulk solid materials such as neutron activated metal or graphite, provided such materials do not exhibit any reactions with the waste container material. However such waste may require some basic conditioning such as size reduction, drying and/or the removal of loose particulate material.

b) Solid waste in a robust shielded waste container

Part of the philosophy behind the use of robust shielded waste containers (generally fabricated from ductile cast iron) for the packaging of LHGW is that it reduces the need for the wasteform to make a significant contribution to waste package performance. This permits a wide range of wastes, beyond those identified in Section 3.2, to be packaged without intimate encapsulation. However, as illustrated in Figure 1, some basic controls on the properties of the waste will be required to ensure that the waste package possesses all of the properties required for it to be shown to be disposable. As a result, some conditioning of waste may be required over and above simple pre-treatment for operational reasons (e.g. size reduction to enable simple loading of the waste into the waste container). This could include drying of the waste, further size reduction and/or compaction to reduce voidage and the removal of challenging components of the wastes (e.g. discrete pieces of irradiated fuel). Treatments such as drying can take place with the waste already in the waste container, by a combination of simple draining followed, if necessary, by drying using heating and/or vacuum extraction methods.

A number of proposals to use robust shielded packages for the packaging of a wide range of wet and dry ILW (i.e. sludges, sand and gravel, ion exchange materials; and dry solid ILW streams, including metal items, filters and soft organic materials) have been endorsed at the Conceptual stage [16].

3.4 Selection of the optimum process for the creation of a non-encapsulated wasteform

During the development of a packaging proposal that could involve the use of a non-encapsulated wasteform the following questions will need to be addressed:

- 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 without the presence of an encapsulant?
- Is the non-encapsulated waste more susceptible to gas generation mechanisms than if it were encapsulated?
- Is the fissile material in the waste more likely to accumulate than if the waste was encapsulated and, if so, does this affect the validity of the relevant criticality safety assessment(s)?
- Are the properties of the waste such that adequate waste package impact and fire accident performance can be achieved?

- Could movement of the waste within the waste container (e.g. during transport) result in damage to the waste container or a significant change to the properties of the waste package (e.g. increased external dose rate)?

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 interim storage facilities 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 LHGW streams is provided in [17 and 18]. To aid in this selection process it is recommended that a waste packager engages with the RWM Packaging Assessment Team at an early stage in the selection of an optimum waste packaging process for a specific waste stream (or waste streams). They 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 waste streams, including radon generating wastes [19], filters [20], closed sources [21] and tritium bearing wastes [22]. Whilst targeted at specific waste types this guidance can also be used as input information into BAT studies during the development of packaging plans for other waste types.

4 Generic requirements for non-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 non-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. 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 hazardousmaterials; 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 materialswith such properties on the performance of the proposed design of waste package. The significance of their presence is assessed as part of the disposability assessment of a proposed waste package design, along with the following additional key performance issues:

- The potential for chemical reactions between the waste and the inner surfaces of a waste container or expansive behaviour of the waste that could result in excessive forces being exerted on the waste container walls and result in loss of waste package performance.
- Evolution of the waste, resulting from chemical, biological and radiation induced processes, may change the properties of the wasteform 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 inoverall safety. Accordingly the consequences of waste evolution should be such that the post-closure safety case requirements 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 ground water 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 ILW waste packages into the backfill is instantaneous (i.e. no credit is taken for any ability of the wasteform to restrict radionuclide leaching). Thus, at present, there are no specified limits on the leaching performance of wasteforms.

5 Guidance on the production of non-encapsulated wasteforms

The key wasteform requirements and 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 clearly best practice to design, demonstrate and manufacture a wasteform that meets all the requirements and criteria specified by the wasteform specification, although it is recognised that 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 one or more wasteform performance requirements is determined as part of the disposability assessment. Guidance on this matter is best obtained on a case by case basis throughearly engagement with RWM in advance of a formal submission for the disposability assessment of a packaging proposal.

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.

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

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 Section 3.1)

To ensure that the performance of a waste package is acceptable during all stages in its long-term management, adequate immobilisation of the mobile components of a waste must be achieved in 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.

How is immobilisation achieved?

The immobilisation of radionuclides in a non-encapsulated wasteform will rely very much on the nature of the waste, and the requirement to achieve immobilisation will limit the wastes that are suitable for non-encapsulation, as discussed in Section 3.2. The following sub-sections discuss the various aspects of immobilisation by non-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?

As discussed in Section 3.1 the words 'immobilisation' and 'encapsulation' have fundamentally different meanings, encapsulation being one means by which the immobilisation of the radionuclides and other hazardous materials associated with a waste can be achieved. In the absence of intimate encapsulation adequate immobilisation will have to be achieved by other means. In the case of a waste package containing a non-encapsulated wasteform it is the provision of physical containment by the waste package as a whole that will ensure whether the wasteform is providing adequate immobilisation.

Figure 1 is of relevance here in that the adequate immobilisation of radionuclides by the waste package can be provided by one or more of:

- some characteristic of the waste itself (e.g. such as in the case of neutron irradiated solid material);
- providing physical containment of the waste as part of the wasteform design (e.g. entombment by a grout annulus); or
- use of a sufficiently robust waste container that will provide physical containment for a suitable period.

Most wastes that are amenable to non-encapsulation will tend not to have characteristics that would result in their associated radionuclides being ‘mobile’ (see Section 3.2). Such wastes would not include components such as particulate matter or liquids at the time of packaging but it is important that their evolution (e.g. corrosion)does not result in the creation of such components over the time scale when immobilisation is required. For waste containing radionuclides with half-lives of greater than a few decades this should extend until at least the end of the GDF operational period. In the WPS for waste packages containing LHGW this period is quantified as 150 years following waste package manufacture, to ensure adequate wasteform performance during transport and the GDF operational period.

The grout enclosure of a non-encapsulated wasteform provides additional containment of the radionuclides and particulate within the waste package provided that the integrity of the grout annulus can be demonstrated for the required time scale. In this way the need to demonstrate immobilisation within the waste itself is obviated.

As discussed above, the use of a robust shielded waste container could remove many of the requirements for the wasteform and will significantly reduce the need to immobilise radionuclides and particulate in a non-encapsulated wasteform. However, the wasteform in such a waste container will still need to provide a degree of immobilisation to ensure adequate package performance, particularly under accident conditions (see below).

How is adequate immobilisation demonstrated?

As part of a submission for the disposability assessment of a packaging proposal waste packagers are required to provide detailed evidence or reasoned argument to demonstrate that a waste conditioning process will result a wasteform with in which radionuclides are adequately immobilised and will remain so for the required period (i.e. 150 years). This should include arguments as to the degree of immobilisation provided by the waste itself and whether any additional containment has been provided (e.g. by pre-treatment of the waste) to enhance such immobilisation.

The evidence required to demonstrate adequate immobilisation could include the following:

- small and large scale testing of the wasteform (see Section 6.2);
- testing or modelling of the waste package to determine radionuclide releases under normal and accident conditions; and
- data to show that evolution of a wasteform over the specified period will not result in physical and chemical degradation that could reduce the effectiveness of the immobilisation (see Section 0 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.

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 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*[4] [26] specify a series of mechanical tests which define the requirements for the impact accident performance of Type B transport packages. This includes exposing the transport package[5] 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 beyond a requirement to withstand 'normal conditions of transport', which include a free drop from a height of 0.3m[6], without 'loss or dispersal of the radioactive contents[7]'.

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 [27]. 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 [28].

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 [29]. 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 [30, 31]:

- For unshielded waste packages; a drop onto a flat unyielding target from a height of 11m, and onto an aggressive feature[8] from a height of 10m.

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[4] Referred to hereafter as the 'IAEA Transport Regulations'.

[5] It should be noted that, in many cases (i.e. for unshielded waste packages), the actual waste package will be protected by a robust transport container which will provide significant additional containment in the event of a release of radionuclides from the waste package.

[6] 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.

[7] 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.

[8] Typically the corner of another waste package.

- 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 of transport and GDF operations can be found in the guidance that supports the WPS [8, 9].

What wasteform properties are required to ensure adequate impact accident performance and how are they achieved?

The release of activity from a waste package in response to an impact accident will be of ‘mobile’ radionuclides, in particulate or gaseous form, so the aim in waste package design should be to limit the inventory of activity in such forms. This will help to ensure that the dose consequences of such activity release is ALARP and within regulatory limits and targets. In the case of a non-encapsulated wasteform this will particularly be achieved by limiting the quantity of activity in particulate form that is associated with the waste.

A thick-walled waste container (such as would be considered a ‘robust shielded waste container) can provide considerable protection in the event of an impact accident, but it may not entirely prevent any release from occurring in all impact accident scenarios. A non-encapsulated wasteform within such container may still, therefore, be required to make some contribution towards ensuring acceptable releases in impact accidents, although this may be limited to eliminating or significantly reducing the presence of fine particulate.

Thin walled waste containers, such as are generally used in unshielded and shielded waste packages, provide only limited containment of particulate activity or protection of the wasteform in the event of an impact accident. In such cases greater demands are placed upon the wasteform itself and additional protection may be required by, for example, ‘entombing’ the waste within a grout annulus with or without super-compaction. Under impact loading damage to an entombed wasteform will primarily occur in the immediate vicinity of the impact. The presence of a ‘clean’ annulus or capping layer of grout around the non-encapsulated waste will distance the radionuclides from the surface of the waste container, thereby reducing the potential for damage to the waste and the resulting generation of active particulate material. The use of a grout annulus and/or capping layer will also increase the distance that such material will have to travel before being released from the waste package.

Using an unshielded or shielded waste container with a non-encapsulated wasteform that has not been grout enclosed places much greater demands on the properties of the waste itself if acceptable releases in the event of an impact accident are to be ensured. For example, the quantity and radionuclides content of any particulate material in the waste would need to be relatively small, and care would need to be taken to ensure that loose waste items could not cause unacceptable damage to the container during an impact accident (the ‘battering ram’ effect).

The use of a robust shielded waste container will provide considerably more protection to a wasteform during an impact accident but attention may need to be paid to the effects of temperature and internal pressurisation on the impact performance of the container.
The potential for brittle fracture of cast iron containers at low temperatures is a particular potential issue here. In this context a knowledge of the material properties, as they affect impact performance, of the waste container material at low temperatures will be required.

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 [32]:

- 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.

In the case of a robust shielded waste package, particular attention may need to be paid to the effects of temperature (e.g. the potential for brittle fracture of cast iron containers at low temperatures)on the performance of the waste package in an impact accident.

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 [26] 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 GDF 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 [28].

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 [33]. For shielded and robust shielded waste packages a fire duration of 60 minutes is currently assumed[9] [32].

What wasteform properties are required to ensure adequate fire accident performance and how are they achieved?

The release of activity from a waste package in response to a fire accident will be of 'mobile' radionuclides mainly in the form of radioactive gases and volatile radionuclides and particulate activity carried in steam produced by the evaporation of water contained in the waste. 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 although, in the case of non-encapsulated wasteforms, heat radiation may also be significant.

There are various mechanisms by which radionuclides can be released from a heated wasteform and subsequently from a waste package via the vent or thermally degraded lid seal:

- Solid radionuclides, notably carbon-14, may react with air inside the waste package to form gases;

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[9] This value may be reduced when work currently underway is completed.

- Radioactive isotopes of noble gases (e.g. krypton) and tritium entrained within the waste could be released by heating of the waste.
- Radioactive isotopes of volatile solid elements (e.g. iodine) and their compounds can become gaseous;
- Activity in particulate form can be carried by steam and other gases created by the evaporation of water or the thermal degradation of other materials in the waste.

The most direct way of limiting the release of radionuclides from waste packages during a fire accident is to control the characteristics of the wasteform. The waste would need to be inert at high temperatures and/or its inventory of volatile radionuclides would need to be small. This would typically include items comprised of steel, concrete, brick, graphite and other inert inorganic solids which would be expected to be reasonably robust under fire conditions.

As in the achievement of other waste package performance requirements the use of a robust shielded waste container lessens the demands on the fire accident performance of a wasteform. However, a number of factors should be taken into account:

- the lid seal may fail due to overheating and/or an increase in the internal pressure of the container. Sudden failure during a fire accident could drive gaseous or fine particulate activity out of the damaged seal.
- The high thermal diffusivity of the waste container and the absence of any insulation (i.e. due to the lack of cementitious grout for example) could lead to rapid heating of the waste and the release of volatile species.
- The presence of excess water in the container could lead to the production of steam and the generation of high pressures. Gases could also be produced by the presence of large quantities of organic materials.

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, including use of a suitable simulant;
- 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 by [32].

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 streams, including:

- specific organic or aqueous liquid waste streams (e.g. oils, solvents, cutting fluid and water based suspensions);
- waste 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.

Liquid (termed bleed water) can be introduced into a wasteform as a by-product if a cement grout enclosure is used and may pool on top of the setting cement unless steps are taken to remove it. Liquid could also be generated during the pre-treatment of the waste, e.g. ‘squeezate’ generated during super-compaction.

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 as part of their long-term evolution.

Why should free liquids be excluded?

The presence of free liquids within the wasteform 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 inhomogeneity within the wasteform;
- increased corrosion of components 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?

The presence of significant quantities of free liquid in a waste would generally suggest that such a waste is not suitable for non-encapsulation as often the best solution to such a property is the mixing of the liquid with a binding agent, such as cement. For wastes containing more limited quantities of free liquid, the use of a sorbent or desiccant may be suitable. If such a material, its long term performance, particularly under the influence of radiation should be known to prevent the possibility of any absorbed liquid becoming desorbed after packaging.

Free liquids can sometimes be effectively eliminated by simple pre-treatment of the waste prior to packaging (e.g. by settling and draining) or by more aggressive drying 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.

During super-compaction trapped liquids may be squeezed out of waste and, if significant in volume, this ‘squeezate’ may have to be collected and receive additional treatment.

Effective immobilisation of some free liquids may be achieved by the waste itself (e.g. tritiated water absorbed on desiccant materials) although it will have to be demonstrated that evolution of such materials would not result in the early[10] release of the liquid.

How is the immobilisation of free liquids demonstrated?

The elimination, minimisation and immobilisation of free liquids in a wasteform can be demonstrated by testing at small and large scale (see Section 6.2), by reasoned argument or by analogy with other wasteforms with proven properties and performance. The consequences of the presence of free liquids in a non-encapsulated wasteform, and the

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[10] i.e.not significantly before the end of the GDF operational period.

measures taken to reduce them will generally have to be considered on a case by case basis during the wasteform assessment.

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. The physical properties of a non-encapsulated wasteforms may be required to contribute to the ability of a waste package to meet such requirements and, as discussed in Section 3.2, this is a factor in deciding whether a particular waste is suitable for such an approach.

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 do wasteforms require mechanical strength?

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 impact accidents.

Most waste packages[11] 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, however the 3 cubic metre drum would not be considered suitable for use with a non-encapsulated wasteform. Accordingly there is no explicit requirement for a non-encapsulated wasteform to contribute to the ability of a waste package to bear stacking loads.

The requirements for a non-encapsulated wasteform to contribute to the impact accident performance of the waste package are discussed in Section 5.1.2.

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[11] 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.

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 macroporosity, consists of discrete unfilled spaces within a wasteform. The inherent nature of a non-encapsulated wasteform is such that it would contain voidage of some kind, the extent of which will depend on the physical properties of the waste.

Why is voidage a problem?

Examples of the possible adverse effects of voidage include the following:

- enhanced local corrosion of the waste container material and potential loss of container integrity;
- enhanced 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;
- the creation of sites for the generation of other hazardous compounds (e.g. metal hydrides);
- the creation of connected voidage that could lead to enhanced leaching/migration of radionuclides from the waste package;
- a reduced confidence in the predictability of waste package performance under accident conditions; and
- long-term slumping/subsidence of waste packages in the GDF post-closure period.

The actual consequences of voidage, in particular the magnitude of any related hazards, will depend on the nature of the waste, its pre-treatment and the waste container design. It may also be the case that voidage in a non-encapsulated 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 take specific steps to reduce voidage may be unnecessary.

How is voidage reduced?

A non-encapsulated waste will by definition have some voidage, and the significance of this would be addressed during the disposability assessment of a packaging proposal. Measures that can be used to reduce wasteform voidage include the pre-treatment of waste (e.g. compaction) or tamping of the waste after placement in the waste container.

Significant wasteform voidage could be eliminated by use of a void filler material (e.g. dried sand). Proposals for the use of such a material would need to be supported by a demonstration that the proposed infilling process could be implemented, when required, and was effective at reducing voidage to an adequate degree (see Section 6.3).

How is the adequate elimination of voidage demonstrated?

Minimisation of voidage is typically demonstrated by reasoned argument (e.g. to be consistent with an ALARP case), by visual inspection of a sectioned wasteform, 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 of 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.

What are mass transport properties and why are they important?

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 non-encapsulated wasteforms the physical properties of the waste 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), and diffusivity.

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 wasteforms classed as low specific activity (LSA) material with the highest permitted activity concentration (i.e. LSA-III).

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.

Processes including the corrosion of components of the waste (notably of reactive metals), radiolysis and biodegradation can generate gas within a wasteform. The gas permeability of a typical non-encapsulated wasteform is expected to be high and gases generated by such a wasteform would be expected to be released rapidly into the voids in the wasteform, and subsequently from the waste package through the vent, if one exists. Because of this, non-encapsulated wasteforms would not usually have a defined permeability.

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. As in the case of permeability, the nature of most non-encapsulated wasteforms means that diffusivity is not likely to be an issue.

c) 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[12]. 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.'* [34].

How can suitable mass transport properties be determined and demonstrated?

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

The macro-voidage within a waste package containing a non-encapsulated wasteform will carry fluids at a rate controlled by their supply (e.g. rate of gas production, or of water inflow from the host rock). Therefore mass transport properties would only be significant if the radionuclide inventory of the waste items is well-distributed and the items are porous. If so their permeability would restrict the loss of radionuclides into groundwater, whereas if the waste items consist of surface contaminated objects their permeability would not provide a barrier to radionuclide migration. The diffusivity of waste items could also contribute to restricting the release of radionuclides distributed throughout the structure. However, these are intrinsic properties of the waste and in most cases cannot be designed.

The addition of inert void filling materials with macro-porosity (e.g. dry sand, glass beads - see Section 6.3), is unlikely to affect the mass transport properties of a waste package to a significant extent. In contrast it should be noted that some potential void filling materials would not be inert (e.g. recent volcanic glasses), and the mass transport properties of a waste package would need to take account of evolutionary processes, which might reduce the permeability as the GDF re-saturates.

In general, the demonstration that a wasteform has suitable mass transport properties would be by reasoned argument by analogy with other waste with proven properties, and/or by empirical evidence of wasteform stability to internal gas generation.

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. Non-encapsulated wasteforms are liable to be more susceptible to the leaching of activity than those that are intimately encapsulated. Accordingly, if a waste contains a significant inventory of water soluble radionuclides (notably strontium-90 and caesium-137), it may not be suitable for non-encapsulation.

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.

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.

Many non-encapsulated wasteforms will be intrinsically heterogeneous due to the following factors:

- packaging of diverse wastes;

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[12] This being a factor of 20 higher than that for LSA-II material.

- the presence of hollow or sealed objects (see also Section 5.2.2); and
- the presence of wastes objects with a range of densities, leading to preferential settling of heavy wastes such as metals at the bottom of a waste 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 so as to minimise heterogeneity. Pre-treatment of a waste stream by the separation of distinctly different waste types may also improve homogeneity (e.g. the removal of high dose rate components such as pieces of fuel or nimonic springs from Magnox fuel element debris). Other techniques that can promote homogeneity include opening/puncturing of hollow or sealed items and size reduction of large flat objects.

How is adequate homogeneity demonstrated?

Homogeneity can be demonstrated by visual inspection of a sectioned simulated wasteform or by tomographic examination of manufactured waste packages (generally using X-rays). 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 $Wm^{-1}K^{-1}$ [35] and these values are used in the thermal modelling of backfilled disposal vaults [36, 37]. 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 [37] shows a relative insensitivity of the thermal performance of the backfilled vaults to wasteform thermal conductivities of up to ~10 $Wm^{-1}K^{-1}$. However, other aspects of wasteform thermal behaviour, in particular fire performance (Section5.1.3), may be adversely affected by higher wasteform thermal conductivity.

The thermal conductivities of non-encapsulated wasteforms could vary greatly, due to the presence of voidage containing air, which has a thermal conductivity more than an order of magnitude less than the minimum guidance value (i.e. 0.025$Wm^{-1}K^{-1}$).

For non-encapsulated wasteforms with low voidage (e.g. tightly packed graphite blocks), the overall thermal conductivity of the wasteform is likely to exceed the guidance value, but this is unlikely to be the case for wasteforms containing a higher proportion of voidage.Steps can be taken to improve the thermal conductivity of a non-encapsulated wasteform, if necessary, by compacting the waste to reduce voidage and/or using a void filler (see Section 6.3).

The presence of small numbers of waste packages with significantly lower thermal conductivities may not,however, disturb the overall thermal performance of a disposal vault containing a majority of waste packages with cement-based wasteforms and backfilled with cementitious grout. The consequences of the inclusion of a large proportion of non-encapsulated and low conductivity waste packages would, however, have to be considered on a case by case basis as part of the disposability assessment of such a packaging proposal.

How can wasteform thermal conductivity be determined?

Several methods are available for determining the thermal conductivity of a wasteform [38]. Steady-state methods are suitable for measuring the thermal conductivity of 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 homogeneous wasteforms, simple small-scale experimental methods can be used; these methods are described in [39]. For more 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.

Acceptable thermal conductivity may be demonstrated by test results, by reasoned argument or by analogy with other endorsed wasteforms 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.

For waste packages containing non-encapsulated wasteforms the only contribution to chemical containment is that which may be made by the waste, which may be small. In the case of a grout enclosed wasteform, the cementitious grout may contribute to overall chemical containment. In both cases the priority should be 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 alpha particle 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. A grout enclosed non-encapsulated wasteform can provide high pH conditions within a wasteform, and may contribute to pH buffering over the lifetime of the package.

The requirement to maintain the high pH of the backfill does not preclude the disposal of wastes or the use of non-encapsulated wasteforms which do not provide pH buffering; the use of such wasteforms will be considered on a case-by-case basis during the disposability assessment of the packaging proposal.

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 waste from a GDF, but wherever possible the disposal of cellulose waste should be minimised to restrict the potential for complexant generation. 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 ILW waste 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[13] 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 compounds which can degrade for form NAPLs (i.e. NAPL pre-cursors)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 LHGW [40].

How can chemical containment be demonstrated?

The concentrations of materials with significance to chemical containment should be minimised prior to waste package manufacture. An essential part of the demonstration of

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

adequate minimisation 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[14] 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 appropriate treatment of such materials is necessary to ensure a safe and stable wasteform. The transport and handling of hazardous materials will be subject to the appropriate regulations as well as a general duty of care.

Hazardous materials may exist at the time of packaging or may be created by a variety of processes following waste conditioning. 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 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. Accordingly the presence or potential generation of such materials will have to be taken into account during the development of a packaging proposal.

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.

In a non-encapsulated wasteform, any pyrophoric materials may have more ready access to oxygen, which may increase the chances of initiating a pyrophoric event or of sustaining subsequent combustion. By contrast, the ready availability of oxygen may permit the material to oxidise in a more controlled manner without leading to combustion.

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

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 wasteform and/or 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 two broad categories: 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 as 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 $\geq$21°C and $\leq$55°C. Flammable gases can arise from several sources. The most common gas to be generated by ILW will be hydrogen, generated by 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.

Although the exclusion of free liquids from a waste package can be achieved by absorption, the presence of sorbed liquids such as flammable solvents could present an increased fire hazard.

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 catastrophic failure 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 packages. Less energetic failures could result in localised damage to the wasteform and 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 and treatment of hazardous materials be demonstrated?

The nature and magnitude of the hazard presented by a specific material will depend on the general nature of the waste, the form of the wasteform and conditioning processes adopted. During the development of a packaging proposal the waste packager should demonstrate that any identified hazardous materials will be removed from the waste or their hazardous properties neutralised. In some LHGW this could 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 assumptions underpinning 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-radioactive[15] gases (in volume terms) are hydrogen, carbon dioxide, methane and hydrogen sulphide. For wastes containing significant quantities of α-emitting radionuclides, the generation of helium can also contribute to the total quantity of gas generated. Gases may be labelled with tritium and/or carbon-14. The release of bulk gases may also carry radioactive gases such as radon-220, radon-222, argon-41 and/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.

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 non-encapsulated wasteforms.

The consequences of gas generation for a non-encapsulated wasteform are generally less than in the case of an encapsulated wasteform, although some of the waste package related consequences will be similar. Also in the case of non-encapsulated wasteforms which are grout enclosed pressurisation of the volume occupied by the waste could lead to

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[15] Although it should be noted that each of the gases listed here could be 'labelled' with radionuclides of hydrogen and/or carbon.

damage to the grout annulus. Such pressurisation could result in the cracking of the grout material if gas is generated more rapidly than it can move through the grout annulus.

a) Gas generation by corrosion

The rate of hydrogen generated by corrosion of metal under anaerobic conditions can be estimated using the 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[16] .

Table 2 lists simplified versions of this equation and from which estimates of hydrogen generation may be determined for metals commonly present in ILW, using representative values for r and A.

Table 2 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 corrosion rate of a non-encapsulated metal may be different to that of the same metal when it has been encapsulated. For example, encapsulation in cement can control the environment to which a metal is exposed (e.g. pH, relative humidity and water availability). In a non-encapsulated waste, the metal may be exposed to different conditions, resulting in different corrosion rates. 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'[17] 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, which gives rise to the production of methane, is the most important microbial process because the degradation of other organic materials

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

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

(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 [41].

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 [22].

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 radioactively labelled 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. Non-encapsulated wasteforms can have certain characteristics that can help to reduce the rate of liberation of tritium and carbon-14 from waste, particularly limited water content, which can reduce rates of corrosion, microbial activity and isotopic exchange.

Some wastes produce radioactive gases by decay, notably radon isotopes from the radioactive decay of actinides. Radon occurs naturally in the decay series of thorium-232 and uranium-238, resulting in radon-220 and radon-222 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 within the waste package, thus retaining the decay products within the waste package. In non-encapsulated wasteforms the only hold-up of radon may be by the waste itself and guidance on this issue can be found in [19].

How are gas production rates determined?

A demonstration that the gas production rates from proposed waste packages will be acceptable will be carried out as part of a disposability assessment. The modelling of waste package gas generation will require wasteform and waste package specific input data and parameters to calculate the gas generation rates during transport and the GDF operational and post-closure periods. Such modelling would need to take account of all of the gas generation processes identified above (i.e. chemical, biological and radiological).

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 and why is it relevant to waste package performance?

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 the nature, quantities and forms of materials present within a wasteform and the environmental conditions that a wasteform is subjected to, including saturation by ground water during the GDF post-closure phase.

The role of a 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.

The wasteform evolution processes are identified in the Wasteform Specification [6] and the relevant DSSC status report [14], their relevance to non-encapsulated wasteforms are discussed below.

a) Organic waste degradation

Organic wastes can undergo radiolytic, chemical, thermal and microbial degradation each of which can lead to the generation of chemical species that have the potential to react with other components of the waste, the waste container or, where used, a grout annulus. Deleterious effects, such as an increased rate of metal corrosion or cracking of a grout annulus could occur, thereby potentially reducing overall waste package integrity.

Common organic materials such as cellulose (e.g. paper, wood and cotton) can degrade by microbial action and alkaline hydrolysis to form acidic species. The extent and rate of microbial and alkaline hydrolysis waste degradation is dependent on water being available within a wasteform.

The radiolytic degradation of chlorinated plastics (e.g. PVC) by alpha radiation can release hydrogen chloride gas, which can dissolve in water to give 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 steel by chloride induced corrosion mechanisms. Further information and guidance on container degradation mechanisms is provided in [14].

b) Corrosion of metals

The corrosion of metallic wastes will generally result in products with a lower density and thereby a greater volume. Table 3lists the volumetric expansion factors[18]for a number of metals that could be present in LHGW.

Table 3 Expansion factors for reactive metals found in ILW

Metal	Corrosion product	Volumetric expansion factor
Aluminium	$Al(OH)_3$	3.2
Iron	Fe_3O_4	2.1
Magnesium	$Mg(OH)_2$	1.8
Uranium	UO_2	2.0

The expansive corrosion of metals is not likely a threat to the integrity of a non-encapsulated wasteform containing loose mixed waste (i.e. that which contains metal mixed with other materials), especially when the access to reactants (i.e. water) is low. However for waste containing a large fraction of reactive metal, especially if it has been compacted, the effects of expansive corrosion may have to be considered. In some instances contact between dissimilar waste metals can accelerate the corrosion rate by galvanic coupling.

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.

c) 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 can 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 has shown that a mean heat output from waste packages of $6Wm^{-3}$ at this time will not cause this target to be exceeded [42]. It has also been shown that small numbers of individual waste packages with significantly higher heat outputs (i.e. up to ~$100Wm^{-3}$) could be accommodated if well distributed about a disposal vault, without the 80°C target being exceeded [43, 44].

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.

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[18] These are conservative values as they do not take into account the consumption of water and the resulting loss of volume.

A number of potential sources of heat generation existin LHGW, 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 knowledge of the specific heat output (i.e. W/TBq) 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 and concentrations of certain 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 [21].

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 equation:

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

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 a significant quantity of corrosion product which could lead to particulate formation or degradation of a wasteform.

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 a significant quantity of gas which could lead to gas pressurisation of a robust shielded waste package or degradation of a grout enclosed wasteform. In practice microbial degradation should be minimised by drying of a waste prior to packaging.

Heat of hydration

The hydration of a cement grout annulus will generate large quantities of heat in a short period of time. Consideration should be given to the effect of such exothermic reactions 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 potential energy being stored in the material. This ‘Wigner energy’ may be released if the graphite is heated. This can result in the release of significant quantities of energy, in the form of heat if the graphite is heated to 50°C or more above the temperature at which the graphite was irradiated. In some cases the irradiation temperatures may have been as low as normal ambient temperature; 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 [45].

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 will minimise the potential for wasteform evolution processes to occur. This should include:

- The selection of the optimum waste packing process by a BAT study will have considered the potential risks posed by wasteform evolution and thereby eliminated any unsuitable combination of wasteform and waste container designs.
- Development and testing of the wasteform and waste packaging process will identify the limits for specific wasteform components such as water and organic content.
- It may be necessary to restrict the quantities of specific wasteform components 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[19]*:*

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 [46].

How can the use of a non-encapsulated 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). For a non-encapsulated wasteform the possibility of the first such scenario is clearly increased over that for a wasteform where the fissile material was immobilised within an encapsulant.

However, CSAs tend to be very conservative and, in particular, make very pessimistic assumptions regarding the mobility of fissile material, its separation from neutron poison such as uranium-238, and the likelihood of accumulation. Indeed, in many cases no benefit is claimed for the effects of encapsulation. For packaging proposals where the 47g[20] generic screening level is not exceeded, no specific consideration of the effects of non-encapsulation 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 could pertain for a non-encapsulated wasteform. For waste packages with fissile material inventories of greater than the relevant lower screening level, it may be possible to use the corresponding 'upper screening level' although in some cases the properties of a non-encapsulated may not permit this. In such cases a package specific CSA may be required.

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

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

6 Guidance on the production of non-encapsulated wasteforms

This section provides guidance on the development and demonstration of a packaging approach for LHGW which includes the use of a non-encapsulated wasteform.

Non-encapsulation will not be a suitable approach for the packaging of many LHGW waste streams. The first stage of the development of a packaging proposal will be to consider a BAT study which, amongst other considerations, should consider the suitability of the waste for non-encapsulation (Section 3.2), the identification of a suitable waste container type (Section 3.3) and packaging process (Section 3.4). This will permit the functional requirements of the packaging plant to be defined, together with its design which will proceed via a number of interdependent, development stages, including:

- definition of the detailed physico-chemical characterisation of the raw waste;
- detailed design of the non-encapsulated wasteform, the packaging plant (including any pre-treatment process) and its operation;
- definition of the wasteform parameters from the packaging plant variables;
- development of a suitable grout formulation if the waste is to be entombed;
- process development work and testing to demonstrate the long term properties and behaviour of the wasteform to ensure that that the final waste packages will satisfy the requirements of the relevant packaging specification;
- scale up of the waste packaging process to full scale; and
- non-active and active commissioning of the packaging plant.

It is acknowledged that whilst the above are of relevance to all types of wasteform (i.e. encapsulated or non-encapsulated) they may not all apply to certain types of non-encapsulated wasteform. For example it may not be possible to 'test' the wasteform if the packaging process involves placing a heterogeneous solid waste inside a container. Similarly there may be no benefit in carry out trials at anything smaller than full scale. The approach therefore to wasteform development will depend very much on the nature of the waste and of the packaging approach.

It is best practice that packaging plant design is progressed in line with the Disposability Assessment process which, as outlined in Section2, is applied at each of the key phases in the development of a waste packaging facility. The stages of the Disposability Assessment process correspond 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 and demonstration of the non-encapsulated wasteform parameter limits

Following the identification of the functional specification of the packaging plant, it is necessary to define the required limits for the various parameters of the wasteform, and demonstrate that they can be achieved using the expected range of process variables which will occur during waste retrieval and packaging. These limits will define the range over which the packaging plant process variables will extend for a particular waste stream, whilst still producing acceptable wasteforms that are compliant with the general requirements of the wasteform specification [6] and the relevant WPS.

The full-scale waste retrieval and the packaging plant processes will have a number of operational variables including the following:

- physico-chemical properties of the as retrieved raw wastes;
- physico-chemical properties of the waste following any pre-treatment prior to packaging; and
- packaging plant process variables (e.g. masses and volumes of waste, the formulation envelope of the grout used to produce the grout annulus).

These variables must be quantified and the ability of the packaging plant process to control the range of variables and produce compliant wasteforms with the defined wasteform parameter limits must be demonstrated.

A packaging plant operating within a defined set of parameter limits can be demonstrated to be capable of consistently producing waste package products which accord with an endorsed Waste Product Specification [47] and are therefore compatible with the requirements for transport to and disposal in a GDF. Such demonstration is based on:

- proven quantitative data on the physico-chemical extremes of the retrieved waste (often referred to as the waste envelope) and quantified conditioning process variables (e.g. quantified limits on the wasteform voidage or moisture content);
- sufficient wasteform development work to demonstrate acceptable product properties of the wasteform (such as the achievement of a moisture content limit for a dried waste, or particulate immobilisation by a super-compaction process); and
- evidence of the production of acceptable wasteform gained during both inactive and active commissioning of the packaging plant.

Operation of the packaging plant to a defined quality management system and plan [48] will provide validation that the waste packages produced over the lifetime of the packaging plant meet the required waste package parameters and quality standards as defined by the relevant Waste Product Specification.

Demonstration of the ability of the proposed packaging plant, working to the defined wasteform parameters, to produce compliant wasteforms is a key requirement of the Interim stage disposability assessment. A submission for the Interim stage disposability assessment of a waste packaging proposal should:

- quantify (as far as possible) the proposed packaging plant process parameters that control the wasteform properties; and
- report the technical research and development work that demonstrates the acceptable performance of the wasteforms produced at the wasteform parameter limits.

6.2 Demonstration of the properties of a non-encapsulated wasteform

The requirements for the properties of all types of wasteform are the same, irrespective of whether they involve encapsulation of not. However, the demonstration that a non-encapsulated wasteform will possess those properties, by the methods typically used in the case of encapsulated wasteforms (i.e. by the use of small scale and large scale trials designed to provide the specific empirical evidence and to demonstrate that specified wasteform parameters can be achieved) may prove problematic. In general, the focus of work to support the demonstration of the properties of a non-encapsulated wasteform will be focussed on an understanding of the nature and behaviour of the waste itself, the manner proposed for its conditioning and the consequences of these for the properties of the proposed waste packages. This will include an evaluation of how those properties will affect the safety of the management of the waste package in both the short term, during interim storage, transport and the GDF operational period, under both normal and accident conditions, and in the longer term during the GDF post-closure period.

Demonstration may have to rely on pre-existing data regarding the form and properties of the waste and/or that produced during the packaging of similar wastes, and may include reasoned argument regarding the nature of the waste, notably the extent of the presence of materials that could challenge the ability of waste packages to satisfy the requirements of both the Wasteform Specification and the relevant WPS.

Trial work could include demonstration of specific aspects of a non-encapsulated wasteform, such as the following:

- properties of an unconditioned waste:
    - well defined physico-chemical properties of the waste, providing a high degree of confidence in the expected evolution of the wasteform and performance of the waste package in accordance with the requirements of the WPS;
    - drying and, where necessary, inerting of wastes that will not undergo degradation and produce gas, or particulate material; and
    - a consideration of the size distribution of any particulate activity associated with the wastes to ensure that quantities of inhalable particles are negligible.
- Evidence of the effectiveness of the waste pre-treatment process(es):
    - ability of a drying process to achieve a defined water content limit; and
    - adequate immobilisation of particulate in a super-compacted puck.
- impact and fire performance of the wasteform (e.g. quantity and size range of particulate produced due to impacts, degradation products released when heated), prediction of corresponding waste package performance; and
- potential wasteform evolution mechanisms.

6.3 The use of void fillers with non-encapsulated wasteforms

Voidage is one of the wasteforms properties for which Generic Specification encourages ‘appropriate control’. For many wastes, that could otherwise be suitable for non-encapsulation, a potential issue could be excessive voidage within the wasteform. As discussed in Section 5.2.2, excessive voidage could lead to a number of waste package issues including enhanced corrosion of the waste and/or the waste container, a reduction in waste package strength, the creation and accumulation of gas or hazardous compounds within voids, reduced predictability of waste package performance under accident conditions, and slumping of stacks of waste packages. The use of ‘void fillers’ has been considered as part of a number of packaging proposals as a means of reducing the consequences of such issues.

A void filler would generally take the form of finely divided inert powder such as sand, fly ash or a crushed mineral such as limestone, the use of glass beads have also been considered. The possibility also exists to use materials with additional beneficial properties such as:

- chemical buffering, to compensate for the absence of cementitious grout in the waste package;
- neutron absorption, to enhance criticality safety;
- acting as a ‘getter’ for gases such as hydrogen; and/or
- fire retardance, to enhance fire accident performance.

The use of a void filler could also aid in the location of waste objects to prevent their movement during transport or GDF emplacement operations. Such movement could result in damage to the waste container and/or increased external waste dose.

Other beneficial effects of the use of a void filler could include:

- improved thermal properties; higher conductivity, general heat transfer and fire accident performance.
- absorption of liquids
- reducing the concentration of oxygen in the waste package, and the rate of oxygen ingress to the waste, thereby reducing corrosion rates;
- reducing waste container/waste interactions;
- provide additional radiation shielding;
- improved impact performance; by acting as a shock absorber;
- improved fire performance by restricting oxygen ingress to the waste; and
- enhancing waste package rigidity.

If a void filler is to be used to enhance the performance of a waste package, arrangements must be made for its effective addition to the wasteform, either during waste package manufacture or prior to the export of waste packages to a GDF. In the latter case this may necessitate removal of the waste container lid, the provision of a port in the lid, or creating an opening (and subsequently sealing it) to admit the void filling material.

7 Summary

For many types of LHGW the most appropriate approach to their conditioning for geological disposal involves intimate encapsulation in a matrix of a cementitious or polymeric material. However, there are some wastes which, either by virtue of their physico-chemical or radiological properties, or the properties of the container in which they are to be packaged, for which such encapsulation is not a prerequisite for their safe and effective disposal.

Not all wastes will be suitable for non-encapsulation in that such an approach could result in a wasteform that would not satisfy the requirements of the Wasteform Specification and, as a consequence, may not permit the manufacture of disposable waste packages.

By considering the consequences of the physico-chemical forms of LHGW, and the chemical properties of the radionuclides they contain, this guidance concludes that solid wastes which are dry, chemically inert and relatively free of fine particulate material and non-fixed surface contamination may be suitable for a packaging approach that includes non-encapsulation.

The assessment of a non-encapsulated wasteform, and of its ability to make the required contribution to the overall performance 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.

The non-encapsulation of waste can take a number of forms and the wasteforms that would result from these can be divided into three broad types, each of which has been shown to be capable of producing wasteforms, and waste packages, with the necessary properties for geological disposal, using either thin-walled or thick-walled waste containers.

The purpose of this guidance is to assist waste packagers with the identification of LHGW which may be suitable for non-encapsulation and the manner in which such wastes should be treated as part of a process for the manufacture of disposable waste packages. Guidance on specific issues that could arise from the non-encapsulation of an actual waste is best obtained through early engagement with RWM, in advance of a formal submission for the disposability assessment of a packaging proposal.

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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 [26]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.

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.

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.’

Managing Radioactive Waste Safely (MRWS)

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

Nirex (United Kingdom Nirex Limited)

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

Nuclear Decommissioning Authority (NDA)

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

Office for Nuclear Regulation (ONR)

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

operational period (of a disposal facility)

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

passive safety

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

plutonium (Pu)

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

post-closure period (of a disposal facility)

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

radioactive decay

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

radioactive material

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

radioactive waste

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

Radioactive Waste Management 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.

ISO 9001 • ISO 14001

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