

# Geological Disposal:

## Guidance on the packaging of radon generating wastes

April 2015



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**WASTE PACKAGE SPECIFICATION AND GUIDANCE DOCUMENTATION  
WPS/902 GUIDANCE ON THE PACKAGING OF RADON GENERATING WASTES**

**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 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 packaging of radium bearing wastes which have the potential to cause the emission of radioactive radon gas from waste packages.

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.

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## **Abbreviations and acronyms used in this document**

ALARP	as low as reasonably practicable
DSS	Disposal System Specification
DSSC	Disposal System Safety Case
DSTS	Disposal System Technical Specification
GDF	geological disposal facility
GWPS	Generic Waste Package Specification
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
ILW	intermediate level waste
IP	industrial package
LLW	low level waste
LoC	Letter of Compliance
MRWS	Managing Radioactive Waste Safely
NDA	Nuclear Decommissioning Authority
OESA	Operational Environmental Safety Assessment
ONR	Office for Nuclear Regulation
PDSR	Package Design Safety Report
RWM	Radioactive Waste Management Limited
SWTC	Standard Waste Transport Container
UKRWI	UK Radioactive Waste Inventory
WPS	Waste Package Specification
WPSGD	Waste Package Specification and Guidance Documentation



# 1 Introduction

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 we assist 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) [1]; 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.

As a means of making the full range of RWM packaging specifications available to waste producers and other stakeholders, a suite of documentation known as the Waste Package Specification and Guidance Documentation (WPSGD) is published and maintained for ready access via the RWM website.

The WPSGD includes a range of WPS for different waste package types together with explanatory material and guidance that users will find helpful when it comes to application of the WPS to practical packaging projects. For further information on the extent and the role of the WPSGD, reference should be made to the *Introduction to the RWM Waste Package Specification and Guidance Documentation* [2].

The requirements for waste packages containing intermediate waste (ILW), and wastes with similar radiological properties, are defined by the *Generic specification for waste packages containing low heat generating waste* [3]. These requirements are applied to the waste packages that can be manufactured using the current range of standardised waste containers (as identified in the *Disposal System Technical Specification* (DSTS) [4]) in the WPS that make up the WPS/300 Series of documents that form part of the WPSGD.

The release of radioactive gases from waste packages poses a challenge to the safety of their transport and disposal and will need to be addressed during the packaging of waste that has the potential to generate such gases. Radon is one of a number of radioactive gases that can be released from waste packages containing ILW and, due to its mobility, chemical inertness, radio-toxicity and the manner in which it is continually generated (i.e. by the radioactive decay of its parent), it presents particular concerns. Fortunately, the relatively short half-lives of the isotopes of radon mean that its release can be reduced by radioactive decay during migration through the barriers presented by the waste package.

This guidance is intended to assist waste packagers in achieving the safe and efficient packaging of radon generating (i.e. radium bearing) wastes, and in the presentation of robust arguments regarding the performance of the resulting waste packages.

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

- Section 2 provides background information on geological disposal in general and the manner in which RWM assesses the suitability of proposed waste packages, for geological disposal. It also summarises the requirements for criticality safety during the transport of waste packages.

- Section 3 provides information on radon and its sources.
- Section 4 discusses why the release of radon from waste packages has consequences for the safety of the transport and geological disposal of waste packages containing radium, and defines screening levels for the radium contents of waste packages.
- Section 5 discusses the behaviour of radon in conditioned waste and how this affects the rate at which it can be released by waste packages.
- Section 6 provides guidance on the packaging of radium bearing wastes in such a manner that will mitigate the consequences of the generation of radon by such wastes.
- Section 7 outlines how arguments can be made to validate the suitability the application of proposed approaches to the mitigation of the release of radon from waste packages
- A glossary of important terms and phrases is presented at the end of the document.

## 2 Background

### 2.1 The concept of geological disposal

The MRWS White Paper [5] sets out the UK Government's framework for the long-term management of the UK's higher activity waste, a key aspect of which is '*geological disposal, coupled with safe and secure interim storage*' of such waste. Whilst the precise manner in which geological disposal would be implemented in the UK is not yet defined we envisage that any approach to long-term management of waste (including disposal) would comprise a number of distinct stages which could include:

- the manufacture of passively safe and disposable waste packages;
- a period of interim surface storage, usually at the site of waste arising or packaging;
- transport of the waste packages to a GDF;
- transfer of waste packages underground and emplacement in the disposal facility;
- back-filling of the disposal areas; and
- eventual sealing and closure of the facility.

The exact nature, timing and duration of each stage would depend on a number of criteria, including the geographical location and host geology of a GDF, as well as the disposal concept selected for implementation for each distinct category of waste.

### 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 both 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 by defining requirements for waste packages which have been derived from the needs of their long-term management.

## 2.3 The transport of waste packages

Whilst the geographical location for a GDF has not yet been identified it is acknowledged that some or all of the waste packages manufactured in the UK will have to be transported, through the public domain, from their site of arising to the GDF. The generic Transport Safety Case [6] assumes that all waste packages will be so transported. These transport operations will be subject to a raft of national and international regulations the most significant of these being the IAEA *Regulations for the Safe Transport of Radioactive Material*<sup>1</sup>[7].

The IAEA Transport Regulations apply to the transport of many categories of radioactive material including wastes with a wide range of specific activities. To ensure a proportionate approach to ensuring the safety of such materials a number of categories of 'transport package'<sup>2</sup> are defined, including:

- Type B - for the transport of radioactive materials in quantities which represent a hazard greater than that permitted for Type A transport packages;
- Industrial Packages -Type IP-2 - for the transport of radioactive materials with low specific activity or low levels of surface contamination; and

It is assumed in the Generic Specification for waste packages containing low heat generating waste [3] that only these types of transport packages will be used for the transport of waste packages containing wastes such as ILW.

The containment philosophy that underpins the safety of the two types of transport package anticipated for the transport of ILW is fundamentally different in the manner by which workers and members of the public are protected from the consequences of the release of radionuclides from transport packages. For Type B transport packages protection is vested in the design of the containment system, whereas for Type IP-2 transport packages it is achieved by controls on the physical form of the contents. To this end the contents of Type IP-2 transport packages are limited to low specific activity (LSA) material and surface contaminated objects, each of which have defined radionuclide limits.

By contrast, no such limits are placed on the contents of Type B transport packages and the IAEA Transport Regulations specify a containment criterion for a Type B transport package when subjected to the tests for demonstrating the ability to withstand accident conditions of transport.

The IAEA Transport Regulations define limits on the contents of transport packages (derived on the basis of a need to limit such properties as external dose rate, heat generation, release of activity etc.) as well as mechanical and thermal testing regimes for the different categories of transport packages. These limits and regimes are used as part of the process for setting limits and performance standards for waste packages in the relevant packaging specifications and, in some cases, they are the most bounding values for all stages of the long-term management of those waste packages.

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<sup>1</sup> Referred to hereinafter as the 'IAEA Transport Regulations'.

<sup>2</sup> The distinction between a 'waste package' and a 'transport package' is important as it influences the manner by which the requirements of the IAEA Transport Regulations are applied. A waste package will, in general, comprise a container in which waste is placed and which is suitable for disposal without further treatment. Some waste packages may require additional physical and/or thermal protection for transport (e.g. a 'transport container'), in which cases the transport package comprises the waste packages and any such protective device. Some waste packages will be capable of being transported without additional protection, and are described as 'transport packages in their own right'.

## 2.4 Types of waste package

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

- For use with ILW and low level waste (LLW) with low specific activity, such as would not generally require the extensive use of remote handling techniques, waste containers incorporating integral radiation shielding<sup>3</sup> 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 qualify as Type IP-2 transport packages in their own right.
- For higher activity ILW, such as would generally require the use of remote handling techniques, relatively thin-walled (i.e. a few mm) metal containers can be used to create *unshielded waste packages*. Because of their high external radiation dose rate, or requirements for the containment of their contents, such waste packages would be expected to be transported through the public domain in reusable shielded transport containers as Type B transport packages.
- For all types of ILW, thick-walled (i.e. many 10's of mm thick) waste containers can be used to provide both radiation shielding and physical containment of their contents, and to create *robust shielded waste packages*. Such waste packages are capable of being stored, transported and disposed of without the need for remote handling techniques or for additional shielding or containment. Depending on their specific design and radionuclide contents robust shielded waste packages could be transported as either Type B or Type IP-2 transport packages.

## 2.5 The assessment of packaging proposals

RWM has established the Letter of Compliance (LoC) Disposability Assessment process [8] to support waste producers in the development of plans to package higher activity wastes. Specifically the Disposability Assessment process is used by RWM to demonstrate that proposals to package waste would, if implemented, result in 'disposable' waste packages. In this context a disposable waste package is one that is compliant with all of the relevant regulations and safety cases for transport to and disposal in a GDF, and in line with regulatory expectations for the long term management of the waste [9].

The Disposability Assessment process also plays an important role in underpinning the generic *Disposal System Safety Case* (DSSC) [10] by providing confidence that the safety cases, which are based on generic assumptions regarding the wastes that are anticipated to be accommodated by a GDF, are compatible with the 'real' waste packages that are being manufactured. The performance of disposability assessments also helps us to show that the disposal concepts considered within the generic DSSC will be appropriate for the wastes they will be expected to cover as well as identifying wastes that could challenge current disposal concepts and allow early consideration of what changes may be required to these concepts to permit these wastes to be accommodated.

Guidance is available on the manner by which waste packagers should prepare submissions for the disposability assessment of packaging proposals [11].

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<sup>3</sup> If needed, to ensure that external radiation dose rates do not exceed the regulatory limits for transport.

### 3 Radon and its sources

Radon is an inert gas, and is the densest of the elemental gases with a density of approximately ten times that of air (i.e. 9.73kg/m<sup>3</sup> at STP). It exists as 29 isotopes with half-lives ranging from a fraction of a microsecond to a few days. Information on the isotopes with the longest half-lives, and therefore with the greatest significance to the transport and disposal of radioactive waste, is shown in Table 1.

**Table 1 Information on significant radon isotopes**

Isotope	Decay mode(s)	Half-life	Parent(s)
Rn-219	$\alpha, \gamma$	4.0s	Ra-223 and At-219 (Uranium-235 series)
Rn-220	$\alpha$	56s	Ra-224 (Thorium-232 series)
Rn-222	$\alpha$	3.8d	Ra-226 (Uranium-238 series)

Despite its short half-life, radon is a naturally occurring element and is present in the atmosphere, mainly as radon-222 from the decay of uranium-238. The concentration of radon in the open air above land ranges from 1 to 100 Bq/m<sup>3</sup>. In caves or aerated mines its concentration is typically 20 to 2,000 Bq/m<sup>3</sup> although values of up to 10<sup>6</sup> Bq/m<sup>3</sup> have been measured in un-ventilated uranium mines [12].

#### 3.1 Radon-222 (radon)

Radon-222, being the longest-lived isotope of all the isotopes of radon is also the isotope with the greatest radiological significance. It is produced by the radioactive decay of radium-226 and since the half-life of the latter is ~1600 years, radon-222 will continue to be produced well into the post-closure period of a GDF. 1TBq of radium-226 produces 7.5GBq of radon-222 per hour, the volumetric equivalent of which is ~10<sup>-10</sup>m<sup>3</sup> per hour at STP.

Radon-222 is an  $\alpha$ -emitter, decaying to polonium-218 and a variety of other radionuclides, before eventually decaying to stable lead-206. The dose consequences of the various radon-222 progenies also need to be considered during any assessment of the radiological impact of radon generation and release although this guidance is limited to considering the issues arising from only radon-222.

Due to the relatively long half-life of radium-226, the rate of generation will remain effectively constant during the transport of wastes bearing radium-226, as well as during the GDF operational period. In the longer term, radon-222 will also be generated by radium-226 arising from the decay of uranium-238 (half-life 4.5x10<sup>9</sup> years) disposed of in the GDF.

#### 3.2 Other isotopes of radon

Two other isotopes of radon are produced by the decay of radionuclides which are present in some waste in significant quantities:

- Radon-220 is generated by the decay of radium-224. However, as the half-life of radium-224 is short (3.66 days), radon-220 may be considered a progeny of



thorium-232 (half-life  $1.4 \times 10^{10}$  years), and is accordingly often referred to as thoron. However, since the inventory of radium 224 in waste is typically small and the half-life of thorium-232 is very long, rates of generation of radon-220 will be very low. Furthermore the half-life of radon-220 is significantly shorter than that of radon-222, so measures to mitigate the release of radon-222 will be at least as effective in the case of radon-220.

- Radon-219 is a progeny of radium-223 (half-life 11.2 days) and effectively a progeny of uranium-235 (half-life  $7.0 \times 10^8$  years). Similar arguments to those made for radon-220 can therefore be applied to radon-219.

This guidance therefore focuses on radon-222, herein after referred to as radon.

### 3.3 The presence of radium-226 in ILW

Much of the ILW in the UK inventory will contain uranium-238 and, as a consequence, will also contain radium-226. The proportion of radium-226 in freshly mined uranium is fixed ( $\sim 0.3\text{g}$  or  $\sim 0.01\text{TBq}$  radium-226 per tonne of natural uranium), it being in secular equilibrium with its parent radionuclides. However, the proportion of radium-226 may be significantly lower in processed and purified uranium such as fuel residues and related wastes, from which it will have been chemically separated prior to fuel manufacture<sup>4</sup>. The radium level in such wastes will therefore not be in secular equilibrium and, since the half-lives of the various radionuclides in the uranium-238 to radium-226 chain are very long (i.e. on a geological timescale), secular equilibrium will take approximately  $10^5$  years to re-establish.

The most significant quantities of radium-226 in ILW will be present in 'technological' wastes', such as medical and industrial sources, that are have been deliberately enriched in either radium-226 or its direct parent radionuclide, thorium-230. Even in the latter case, the time to reach equilibrium with radium-226 is several thousand years. In general significant radon generation is likely only for materials deliberately enriched in radium-226. However for wastes containing a significant inventory of thorium-230, radium-226 in-growth may be significant on the timescale of relevance to transport and the GDF operational period (i.e. up to a few hundred years).

The 2013 UK Radioactive Waste Inventory (UKRWI) [13] identifies a wide range of ILW waste streams which contain radium-226. The total radium-226 in the ILW and LLW expected to arise by 2200 is 8.5TBq. This value translates to a mean concentration of  $\sim 3 \times 10^{-5}$  TBq per cubic metre of conditioned waste but this is somewhat misleading as a closer examination of the data in the UKRWI shows that  $\sim 90\%$  of the total radium-226 inventory is contained in a single ILW waste stream, which comprises only  $\sim 0.01\%$  of the total conditioned volume of ILW. When this wastestream is removed, the mean radium-226 concentration of the remainder of the ILW inventory is an order of magnitude lower (i.e.  $\sim 4 \times 10^{-6}$  TBqm<sup>-3</sup>).

Appendix A identifies the ILW waste streams with the highest total radium-226 inventories and concentrations (in TBq/m<sup>3</sup>) and shows that, in general, the ILW waste streams with the largest inventories of radium-226 comprise:

- radiation sources containing radium compounds;
- medical items such as radium needles;

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<sup>4</sup> As a consequence the waste products of uranium purification are enriched in radium-226 although such materials (known as 'tailings') are managed at the uranium mine or purification facility and no significant quantities exist in the UK.

- 'luminised' items (i.e. items painted with radium compounds);
- scrap material produced during the manufacture of radiation sources; and
- laboratory glassware and other materials contaminated with radium-bearing solutions (e.g. precipitated radium salts).

## 4 The potential consequences of radon release from waste packages

This Section explains why the release of radon from waste packages raises safety issues for the transport and disposal of waste packages containing radium-bearing wastes. It also defines a series of *screening levels* for waste packages which can be manufactured using the standardised designs of waste container which are identified by the Disposal System Technical Specification (DSTS) [14]. A screening level is a value defined to provide guidance to waste package designers by indicating a radionuclide inventory or waste package property (e.g. heat output) which would be expected to satisfy the relevant requirements of the packaging specifications without additional justification. In many cases the actual limiting value for a waste package can be significantly higher than the screening level, when other factors are taken into account.

### 4.1 Transport safety

Releases of radon during the transport of waste packages could result in radiation exposure to transport workers and members of the public. In this context the limits defined by the IAEA Transport Regulations apply, specifically those limiting the release of radionuclides, including those in gaseous form, from transport packages during normal operations and under specified accident conditions. The requirements of the IAEA Transport Regulations on the transport of waste packages containing ILW are taken into account in the Generic Specification for waste packages containing low heat generating waste [3], and this is applied to waste packages containing radon generating wastes in the manner explained below. It should however be noted that, in addition to the limits imposed by national and international legislation, the releases of activity during transport operations should always be as low as reasonably practicable (ALARP).

As discussed above it is assumed that waste packages containing ILW will generally be transported as Type IP-2 transport packages in their own right or as part of a Type B transport package, when carried in a transport container. These two transport configurations are considered separately below.

#### 4.1.1 Type IP-2 transport packages

The IAEA Transport Regulations do not define quantified limits for the release of activity (including radioactive gases) from Type IP-2 transport packages under normal conditions of transport. The Generic Specification however interprets the requirement to '*prevent loss or dispersal of the radioactive contents*' from such transport packages as being the same containment requirement as that specified for Type B transport packages under the same conditions. In the case of radon-222, which has an  $A_2$  value of  $4 \times 10^{-3}$  TBq, the limit  $10^{-6} A_2$  per hour translates to a maximum release rate of  $4 \times 10^{-9}$  TBq/hour (which would be emitted by  $5.4 \times 10^{-7}$  TBq of radium-226).

Applying such a limit to the quantity of radium-226 in a transport package makes no allowance for the decay of radon within the waste package as it assumes that all of the gas generated escapes directly from the package, for example through the engineered vents. Accordingly this value is a very pessimistic limit, especially for unvented waste packages (or those for which the vent is sealed during transport) or those fabricated from concrete for which significant hold-up of radon can be assumed.

It should also be noted that the values quoted above do not take into account any contribution from other radioactive gases<sup>5</sup> and the presence and release of such gases would clearly lead to a reduction in the allowable radon release rates.

Notwithstanding these arguments, the value of  $5.4 \times 10^{-7}$  TBq can be used as a screening level for the permitted inventory of radium-226 in a waste package transported as a Type IP-2 transport package in its own right.

#### 4.1.2 Type B transport packages

As noted above the IAEA Transport Regulations place a limit of  $10^{-6}$  A<sub>2</sub> per hour on the release of activity from a Type B transport packages under normal conditions of transport. In the case of waste packages carried within a nominally sealed transport container, it is the release of activity from the transport container itself that must be considered against this limit as any activity released by the waste package will accumulate in the cavity of the transport container and will gradually leak out through the container lid seal.

The existing designs of unshielded waste packages (i.e. the 500 litre drum, 3 cubic metre box and drums and the MBGWS<sup>6</sup> Box) are expected to be transported within a standard waste transport container (SWTC). Using a standardised leak rate for the SWTC sealing system and assuming an internal pressure of 800kPa (the maximum assumed for transport) it is possible to determine the maximum allowable radon hold-up in the cavity which would result in a leak of  $10^{-6}$  A<sub>2</sub> per hour from the transport package. Assuming that such a hold-up will accumulate over the period that the transport container is sealed (assumed to be a maximum of 28 days) allows a maximum radon release rate for the waste package(s) to be determined, together with the radium-226 inventory that would lead to such a release.

Table 2 lists the allowable radon release rates and corresponding radium-226 inventories for waste packages manufactured using each of the standardised designs of unshielded waste container, when carried in each of the three variants<sup>7</sup> of SWTC.

As in the case of Type IP-2 transport packages the values given in Table 2 are pessimistic in that they do not take into account any decay of radon within the transport container cavity or hold up of radon within the waste package (notably the wasteform). The former effect would be significant since the half life of radon-222 (i.e. 3.8 days) is significantly less than the period for which the transport container is sealed (i.e. up to 28 days), and that significant decay of the radon released from the waste packages will occur in the transport container cavity during the transport operation. However, since radon will be continually generated, secular equilibrium of the radon concentration in the transport container cavity will occur ~10 days after sealing of the container. This effect is taken into account in determining the allowable radon release rate from the waste packages into the cavity which are given in Table 2.

The values in Table 2 do not take into account contributory releases from other radioactive gases, but they do act as pessimistic screening levels for the radium-226 inventory of unshielded waste packages.

For waste packages which are Type B transport packages in their own right (i.e. those which are not carried in a sealed transport container), the same methodology that is applied to Type IP-2 transport packages above applies.

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<sup>5</sup> Such as tritium and its gaseous compounds, or carbon compounds which include carbon-14 atoms.

<sup>6</sup> Miscellaneous Beta Gamma Waste Store

<sup>7</sup> These having nominal shielding thicknesses of 70, 150 and 285mm and differing internal cavity volumes.

**Table 2 Screening levels for unshielded waste packages carried within a SWTC**

Waste package type	Variant of SWTC					
	SWTC-70		SWTC-150		SWTC-285	
	Rn-222 release rate	Ra-226 inventory	Rn-222 release rate	Ra-226 inventory	Rn-222 release rate	Ra-226 inventory
	TBq/hr	TBq	TBq/hr	TBq	TBq/hr	TBq
500 litre drum <sup>1</sup>	6.4x10 <sup>-8</sup>	8.5x10 <sup>-6</sup>	1.3x10 <sup>-7</sup>	1.7x10 <sup>-5</sup>	7.5x10 <sup>-8</sup>	1.0x10 <sup>-5</sup>
3 cubic metre box <sup>2</sup>	8.4x10 <sup>-8</sup>	1.1x10 <sup>-5</sup>	3.5x10 <sup>-7</sup>	4.7x10 <sup>-5</sup>	1.3x10 <sup>-7</sup>	1.7x10 <sup>-5</sup>
3 cubic metre box <sup>3</sup>	9.0x10 <sup>-8</sup>	1.2x10 <sup>-5</sup>	3.6x10 <sup>-7</sup>	4.8x10 <sup>-5</sup>	1.3x10 <sup>-7</sup>	1.7x10 <sup>-5</sup>
3 cubic metre drum	2.2x10 <sup>-7</sup>	2.9x10 <sup>-5</sup>	4.9x10 <sup>-7</sup>	6.5x10 <sup>-5</sup>	2.6x10 <sup>-7</sup>	3.5x10 <sup>-5</sup>
MBGWS box <sup>4</sup>	-	-	8.2x10 <sup>-8</sup>	1.1x10 <sup>-5</sup>	-	-

Notes for Table 2:

- <sup>1</sup> Values are for each of four waste packages carried in a SWTC.
- <sup>2</sup> Side lifting variant of 3 cubic metre box with plan dimension of 1710mm.
- <sup>3</sup> Corner lifting variant of 3 cubic metre box with plan dimension of 1665mm.
- <sup>4</sup> Waste packages which comply with the dimensional outline of the MBGWS Box can only be carried in a SWTC-150.

## 4.2 GDF operational and post-closure safety

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

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

The release of activity in gaseous form from waste packages has the potential to cause on- and off-site dose during both the GDF operational and post-closure periods. The generic Environmental Safety Case [15] identifies radon-222 as one of the most significant radionuclides (along with tritium and carbon-14) that could be released from waste packages in gaseous form and lead to off-site dose. The generic Operational Environmental Safety Assessment (OESA) [16] uses a value of 0.01mSv/year (derived from the 2009 Statutory Guidance to the Environment Agency [17]) as a target for the maximum dose to the most exposed group of members of the public due to routine discharges from a GDF. This value is used to define screening levels for the release of gaseous radionuclides from waste packages on the basis that if these levels were

exceeded by the entire ILW inventory (assumed to comprise ~360,000m<sup>3</sup> of conditioned waste) the 0.01mSv/year target would be exceeded. In the case of radon, this leads to a value of 150Bq/hour per cubic metre of conditioned waste, and this can be applied to waste packages manufactured using the standardised designs of waste container, as shown in Table 3.

**Table 3 Screening levels derived from operational and post-closure constraints**

Waste package type	Rn-222 release rate	Ra-226 inventory
	TBq/hr	TBq
500 litre drum	$7.5 \times 10^{-11}$	$1.0 \times 10^{-8}$
3 cubic metre box	$4.5 \times 10^{-10}$	$6.0 \times 10^{-8}$
3 cubic metre drum	$3.7 \times 10^{-10}$	$4.9 \times 10^{-8}$
MBGWS box	$7.0 \times 10^{-10}$	$9.3 \times 10^{-8}$
2 metre box	$8.0 \times 10^{-10}$	$1.1 \times 10^{-7}$
4 metre box	$1.5 \times 10^{-9}$	$2.0 \times 10^{-7}$
6 cubic metre Box	$8.0 \times 10^{-10}$	$1.1 \times 10^{-7}$

### 4.3 Summary

The screening levels for the radium-226 inventory of waste packages derived for transport and for the GDF operational and post-closure periods are summarised in Table 4, this shows that in all cases the latter are more bounding.

Comparison of these values with the UKRWI data shows that 40 ILW waste streams with a total projected conditioned volume of ~34,000m<sup>3</sup>, (~10% of the total ILW inventory) have radium-226 inventories in excess of  $2 \times 10^{-8}$  TBqm<sup>-3</sup>, a concentration that would lead to an unrestricted radon emission rate equal 150Bq per hour per cubic metre, the screening level defined by the Generic Specification.

It should be emphasised that the screening levels are not hard limits on the allowable radium-226 inventories for waste packages. They provide an indication of the inventories below which a waste packager will not be required to demonstrate that specific consideration has been given to the consequences of the presence of radium-226 within proposed waste packages. The screening levels are however very conservatively derived, and do not claim any benefit from any degree of waste package hold-up of radon that could reasonably be expected from the use of conventional packaging methods. Accordingly, it may be allowable to package wastes with significantly higher inventories of radium-226 without incorporating specific measures to maximise this hold-up. This aspect is explored further in subsequent Sections of this guidance.

**Table 4 Comparison of radium-226 screening levels for transport and GDF operational and post-closure periods**

Waste package type	Screening Levels for radium-226 inventory (TBq)	
	Transport	GDF operational and post-closure
500 litre drum	$8.5 \times 10^{-6}$	$1.0 \times 10^{-8}$
3 cubic metre box	$1.1 \times 10^{-5}$	$6.0 \times 10^{-8}$
3 cubic metre drum	$2.9 \times 10^{-5}$	$4.9 \times 10^{-8}$
MBGWS box	$1.1 \times 10^{-5}$	$9.3 \times 10^{-8}$
2 metre box	$5.4 \times 10^{-7}$	$1.1 \times 10^{-7}$
4 metre box	$5.4 \times 10^{-7}$	$2.0 \times 10^{-7}$
6 cubic metre Box	$5.4 \times 10^{-7}$	$1.1 \times 10^{-7}$

## 5 The behaviour of radon in conditioned waste

As discussed above, radium-226 is the only significant source of radon in ILW. It will be present in small quantities in many waste streams, notably those containing uranium fuel residues, and in greater quantities in wastes arising from processes where it has been deliberately concentrated.

The manner of the generation of radon, by the radioactive decay of radium-226, is such that there is a tendency for atoms of radon to decay *in situ* to a solid daughter product. However, particularly in cases where the generation rate is high (i.e. in materials with a high radium-226 inventory), the radon atoms can migrate from its original location and may be released into the atmosphere before it decays to a solid daughter.

Three parameters are useful when considering the migration of radon within a waste or a wasteform, or how it will be released from a waste package:

- *diffusion coefficient*: The property of a material that characterises diffusive migration, relates the molecular flux of a diffusant and the applied concentration gradient.
- *emanation coefficient*: Characterises the mitigation offered by radon decay during migration through an item of waste to a free surface. Defined as the fraction of the total radon generated that is released by the waste, wasteform or from a waste package.
- *effective generation rate*: The observable rate at which radon is produced by an item containing radium- 226. The product of the actual radon generation rate and the emanation coefficient.

The matter of the in-package behaviour of radon and the derivation of emanation coefficients for specific design of waste packages is dealt with extensively in [18], this section provides a summary of the information in that document.

### 5.1 Migration of radon in waste

Measurements of radon emanation coefficients in solid items of waste have yielded values of between  $4.0 \times 10^{-1}$  and  $2.8 \times 10^{-3}$  depending on the physical and chemical form of the waste, the average value for a series of samples being  $9.6 \times 10^{-2}$  [19]. The dimensions of radium bearing objects will be significant in this context. Radiation sources and scrap are assumed to be essentially metallic with typical dimensions of the order of 0.01-0.1m. In contrast, precipitated radium salts will be crystalline or amorphous particles with uncertain dimensions, perhaps as small as 10-100 $\mu$ m and the higher surface area of such items will lead to higher emanation coefficients.

### 5.2 Migration of radon in wasteforms

The migration of radon in cementitious materials may take place by a number of mechanisms [20]. The majority of the published data refers to the diffusion of radon through construction materials and is related to reducing the rate of radon entering buildings. The migration of radon is commonly characterised by an effective diffusion coefficient, determined from observed radon ingress and a known concentration gradient.

Data relating to radon diffusion in cementitious grouts of the types commonly used in the packaging of radioactive wastes is available in [18] which, when taken together with other measurements in similar material [21, 22, 23] indicate that intrinsic diffusion coefficients for radon lie in the range  $10^{-7}$  to  $10^{-9}$  m<sup>2</sup>/s. These values are consistent with the information on gas diffusion in cements and concretes published elsewhere (e.g. [24]).



Typical values for radon emanation coefficients for cementitious materials are given in Table 5 ([25, 26]).

**Table 5 Typical radon emanation coefficients**

	Range of emanation coefficients (m <sup>2</sup> /s)
uranium mill tailings	0.05 to 0.30
cement	0.008 to 0.085
brick	0.008 to 0.16
particulate materials (e.g. pulverised fuel ash, blast furnace slag and gypsum)	0.002 to 0.21

The migration of radon through cementitious materials is strongly affected by the presence of cracks [20]. Consequently, the production of wasteforms which are effectively monolithic is important in achieving a high radon emanation coefficient.

There is an extensive literature reporting measurements of the diffusion of radon through polymer membranes, these report diffusion coefficients for polymeric materials such as polyesters, PVC, polythene and polypropylene, typically in the range  $10^{-11}$  to  $10^{-13}$  m<sup>2</sup>/s (i.e. a factor of  $\sim 10^4$  lower than those reported for cementitious materials)

The source of the polymer may be significant, with materials from different manufacturers exhibiting different permeation coefficients. Where materials may be manufactured in hard (more extensively cross-linked) or soft forms, the hard form generally has a lower permeation coefficient. An example of such a material is PVC [27].

The radon diffusion coefficient is strongly temperature dependent for some polymers. For example, the diffusion coefficient for polypropylene increases by an order of magnitude (i.e. from  $5 \times 10^{-13}$  to  $5 \times 10^{-12}$  m<sup>2</sup>/s) as the temperature is increased from 20°C to 40°C [28]. It has been reported that the gamma irradiation of polyester and polypropylene decreases the diffusion coefficient by a factor of about two for doses up to 0.1MGy [29].

### 5.3 Release of radon from waste packages

The OESA [16] calculates the total radiation doses due to the radon produced by the entire GDF inventory of radium-226 in ILW by using a generic emanation coefficient of  $2.0 \times 10^{-3}$ . This value derives from historic work carried out to determine emanation coefficients for 500 litre drum waste packages containing radium bearing wastes encapsulated using cementitious materials [18, 30]. The value of  $2.0 \times 10^{-3}$  was deemed to be 'cautious' and the same work provided estimates of as low as  $4 \times 10^{-5}$  for 'enhanced' designs of 500 litre drum waste package, such as those with an inactive cement annulus surrounding the active wasteform.

## **6 Guidance on the packaging of radium bearing wastes**

### **6.1 Waste streams with low radium inventories**

Waste packages which have radium-226 inventories below the screening levels listed in Table 4 will not raise any safety concerns at any stage during their long-term management. However, in order to ensure that radon release rates and consequent doses are ALARP, good practice should still be followed in the design of all waste packages containing radium-226.

Being chemically un-reactive, radon can migrate relatively rapidly in some materials and careful selection of the waste conditioning process(es) and materials should be followed during waste package design to ensure that an adequate reduction of the effective generation rate will be achieved. This could entail:

- use of common waste conditioning methods, such as use of cementitious grouts, or supercompaction and grouting;
- use of a capping grout [31];
- use of container materials with good longevity under appropriate storage conditions, such as stainless steels;
- the optimisation of the gas vent size (if fitted).

### **6.2 Packaging of wastes with significant radium inventories**

Waste packages which have radium-226 inventories which exceed the screening levels listed in Table 4 may require specific consideration as to the consequences of the emission of radon. As well as the simple generic examples of best practice listed above, additional features may be required in waste package design, and an explicit case may need to be made by the waste packager to justify the proposed packaging method. Early dialogue with RWM is, therefore, recommended to establish the actual requirements and to explore potential approaches.

The remainder of this guidance provides information on packaging methods that could be considered and on methods for assessing and demonstrating waste package performance. Where a case needs to be made, consideration and justification of the measures applied to ensure compliance with limits on the rate of radon release, based on its detailed assessment of proposals, will be required. The design and implementation of such measures will ultimately be the responsibility of the waste packager, with advice and assessment being provided by RWM.

### **6.3 Issues to consider**

A number of widely different approaches can be applied to the packaging of different types of ILW (i.e. those with different physical, chemical and radiological properties). The following issues are likely to be of concern in the development of packaging methods for radium bearing wastes:

- identification of the radium bearing items and, where possible, the estimation or measurement of the effective radon generation rate from those items. This should include a consideration of the evolution of such items following packaging;
- evaluation of the degree of mitigation required of the packaging, such as the encapsulant or waste container and associated features;

- specification of materials and, in particular, provision of robust migration rate data for the packaging materials under relevant conditions (degree of water saturation, age, extent of irradiation etc);
- particular consideration of the sealing of containers and the robustness of the packaging against manufacturing defects;
- consideration of the possibility of cracking or degradation damaging the barrier properties of the materials or design features used, including the evolution of the waste package over time (desiccation, extent of irradiation etc);
- generation of bulk gases in the same container, from degradation of wastes and any added encapsulants, and their effect on sealed or poorly vented containers, and on radon retention;
- provision of data regarding the properties of the packaging materials, obtained under relevant conditions (waste packagers are advised that properties are best measured directly, although available literature data are acceptable if they can be shown to be relevant);
- validation of models and arguments, ideally through measurements on packaged wastes or simulants (RWM has developed models for assessment purposes, which may be of value to waste packagers).

Although some data on the properties of waste or packaging materials are available from the literature, these are not necessarily relevant to packaged wastes. The value of experimental measurements for the materials to be used is therefore emphasised, as is that of measurements of the rate of radon generation, effective generation rates and the rate of radon release (as necessary).

In all cases, the waste packager will need to demonstrate that the performance of the proposed packaging method is suitable and likely to remain so over an appropriate period of time.

The various methods for mitigating the rate of radon release are discussed in more detail below. Further guidance on the presentation and validation of the arguments to support the use of a particular method is provided in Section 7.5.

## **6.4 Packaging of waste**

### **6.4.1 Use of different types of waste package**

As discussed in Section 2.4 the range of waste container designs which are currently being used for the packaging of ILW are used to manufacture waste packages which fall into three basic types; shielded, unshielded and robust shielded. Each type of waste container can be used for the packaging of radium bearing waste but the following points need to be considered:

- Shielded waste packages are generally transported without a protective overpack which means that there is no physical barrier against the release of radon from the waste package if the container is vented. However, vents can be sealed during transport.
- Unshielded waste packages are generally transported in nominally sealed transport containers which retain most of any radon released by the waste package (see Section 4.1.2).
- Robust shielded waste packages are generally used for the packaging of wastes in a non-encapsulated form, so the wastform will provide little retention of any radon produced (see Section 6.4.3).

## 6.4.2 Waste sorting and identification

In many cases, the radium inventory of a waste is confined to particular discrete items, for example radium sources. The sorting of such items for separate packaging potentially provides a significant reduction in the amount of material for which special packaging measures might be necessary. Furthermore, materials that might give rise to significant bulk inactive gas generation, and hence bulk gas advection, may be segregated from radium bearing items, thereby providing greater flexibility in the packaging concepts available.

Waste packagers are also referred to *Specification for Waste Package Data and Information Recording* [32]. It will be necessary to generate realistic and justifiable records for wastes, and this is likely to require examination of stored wastes to generate such a record where inadequate records exist, before packaging for disposal.

## 6.4.3 Retention of radon by the waste

Radon will be retained within some types of waste, giving an effective radon generation rate that is significantly lower than the rate derived directly from the radium-226 inventory. This reduction can be characterised by the emanation coefficient, the ratio of the observed and expected radon generation rates. For some types of waste, the emanation coefficient may be substantially less than unity due to the physical nature of the waste.

Where the emanation coefficient of the waste is substantially less than unity, it may be possible to demonstrate that, although the generation rate calculated from a known radium-226 inventory is greater than limits, the effective generation rate is nonetheless consistent with such limits due to retention of radon by the waste itself. If this is the case, no additional credit need be taken for any mitigation of the rate of radon release by the packaging. The degree of retention by the waste can range from granular materials (low retention) to engineered objects such as sealed sources (high retention)<sup>8</sup>.

The presentation of an argument based on emanation coefficient will require waste packagers to demonstrate the degree to which radon is held up in the waste. The review of data has suggested that a reasoned argument is unlikely to be sufficient and, therefore, experimental evidence will be required. This should take the form of measured effective generation rates from the waste.

The ability of a waste to retain radon may be threatened by the evolution of the waste itself and by changes in the environment after packaging. Waste packagers should, therefore, demonstrate an understanding of the evolution of the waste under appropriate conditions and its impact on radon retention. This should include consideration of the conditions that may be experienced during transport; for example increases in temperature.

## 6.4.4 Conventional packaging methods

Historically the 'conventional' approach to the packaging of ILW has involved the intimate grouting of wastes with a cementitious or polymeric material, or the use of a grout annulus enclosing compacted wastes. It may be possible to generate suitably validated models to show the degree of radon retention by the wasteforms, particularly the encapsulant materials, but this may not be a simple exercise. RWM has commissioned modelling work to assess the effectiveness of these conventional methods in the mitigation of radon release rates [33]. This work suggests that significant benefits can be achieved by the use of a conventional approach to packaging, and that emanation coefficients of as low as 0.015 for intimately grouted wastes and 0.001 for annular grouted wastes could be achieved. However, these values are very dependent on grout porosity, and less porous

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<sup>8</sup> If the integrity of such sources can be assured until the end of the GDF operational period.

grouts would yield significantly higher values for emanation coefficient (0.47 and 0.38 respectively). Uncertainties associated with waste heterogeneity and ageing of grout encapsulants will also need to be considered.

#### 6.4.5 Use of engineered features

In addition to the use of encapsulants, it may be possible to engineer other features into the wasteform or waste container design which will provide barriers to radon migration. These could include reduced container vent sizes, decay tubes or filters.

A gas vent will usually be required to release bulk gases and thus radon releases may also occur. Nevertheless, it will be best practice to minimise the vent size. If this is insufficient to control radon release, and in many cases this is unlikely to be sufficient, consideration could be given to use of decay tubes or absorbers as part of the container or wasteform component design. A decay tube is designed to provide a long pathway for radon diffusion, thus allowing decay to occur rather than release. However, for such a method to be successful, consideration would need to be given to:

- the effect of gas advection speeding radon migration, due to bulk gas generation and release;
- the physical robustness and longevity of any engineered feature.

#### 6.4.6 Containerisation of waste in gas-tight packaging

The packaging of radium bearing waste in a gas tight container could provide a solution to the issue of radon generation. It provides the clear advantages that the rate of radon release will be (effectively) zero over the time period<sup>9</sup> for which integrity can be guaranteed, and that the justification of the expected performance is likely to be straightforward. However, the *Wasteform Specification for wastes packages containing low heat generating waste* [34] includes 'sealed containers' in the list of hazardous materials to be excluded from wasteforms, so if such containerisation was to be considered, its wider implications would need to be assessed.

Of particular concern would be the effects of gas pressure on container integrity, this could be particularly so for very small containers where significant pressurisation could occur over the period of interest, potentially threatening the integrity of the container<sup>10</sup>. Excessive pressure within a container may threaten the integrity of seals. This is particularly the case for polymer-based materials, which are relatively weak. To show that a proposed gas-tight containment method is acceptable, a waste packager would need to demonstrate that all potential gas generation mechanisms have been considered, and that the volumes of gas that may be generated within the container have been shown to be acceptable. It should also be noted that, if an approach involving the use a gas-tight component is proposed (either the waste container or sealed internal vessels within the wasteform), this would, as a minimum, require a convincing argument of gas-tightness prior to transport. There may also be implications in terms of the maintenance of integrity during the GDF operational period.

Pressurisation by radon is unlikely to be of concern as in general the volume of the radon generated from a most radium bearing wastes is small. For example, 1TBq of radium-226 produces a volume of  $1.2 \times 10^{-6} \text{m}^3/\text{y}$  of radon at STP although, due to the decay of the radon to non-gaseous progeny, the equilibrium pressure resulting from this generation will be very

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<sup>9</sup> A representative time period would need to at least cover the operation phase of the repository.

<sup>10</sup> It should be noted that such behaviour has actually been observed in storage containers used for radium-rich waste at RSRL, although it is likely that the gas causing such pressurisation is from the radiolysis of water or other materials rather than radon (see below).

small. The simultaneous generation of helium (due to the  $\alpha$ -decay of radium-226 and its progenies) is also likely to be very small (1TBq of radium-226 will generate  $\sim 6 \times 10^{-6} \text{m}^3/\text{y}$  of helium in total) but, unless the helium is released, pressure will increase with time as, unlike radon, the helium will not decay. Despite these relatively small volumes, the consequences of a sudden release of a volume of gas containing radon at secular equilibrium would need to be assessed.

Other sources of gas generation could, however, be more significant. These could include wastefrom corrosion, microbial decay of organic materials, and/or the radiolysis of water and organic materials (noting the radium-226 has a very high specific activity which could lead to significant radiolysis of certain materials). Such mechanisms of gas generation will be greatly reduced if water is excluded from the waste, as it is an important reactant for both of them. It is therefore recommended that the exclusion of any source of water be adopted as a requirement for such containerised waste. Organic materials should also be excluded from the waste itself, but where a polymeric material is used to form the primary container, degradation of the container should be considered. If sterility can be guaranteed, then it may be possible to rule out microbial degradation of organic materials, and the consequential production of carbon dioxide and methane.

Other potential hazards arising from the use of a gas-tight container could be the generation of fine particulates and the formation of hazardous materials (e.g. pyrophoric materials such as uranium hydride).

Containers fabricated from metal or polymer can be used, the former has precedents in the manufacture of sealed sources, whereas the latter might be considered analogous to food packaging or the use of membranes to exclude radon from dwellings. The container material should have a well documented low permeability and diffusion coefficient (or permeation coefficient) for radon through the intact material. However, the performance of such a container will then depend not on the properties of the intact material but on the integrity of the container seals or manufacturing joints. Waste packagers are advised that arguments based upon a sealed container should consider not only the properties of the materials but also the means of sealing the container and how the expected performance can be guaranteed over relevant timescales.

A number of commercial polymeric materials are potentially suitable for use in the packaging of radium bearing wastes. These include aluminised polyethylene terephthalate (PET or Mylar) and other polymeric materials used in food packaging, and membranes intended for use in the construction of radon-proof walls and flooring. Examination of manufacturers' information for candidate materials often provides details of radon migration rates for the materials, and such data may be cited to demonstrate the expected performance of the conditioned waste. However, it is recommended that the provenance of such data be examined to ensure that it is of suitable quality.

#### **6.4.7 Multi-barrier approaches**

Multi-barrier approaches to the design of a wastefrom or the waste package as a whole, which progressively reduce radon migration through each barrier without vulnerability to failure of a single barrier, could provide a high degree of confidence in radon retention by a waste package. Such designs may also allow for some release of other gases and for reduced sensitivity to evolution of the waste packages during storage. Such an approach could involve the use of semi-permeable barriers, either in the form of encapsulants or use of other engineered features such as decay tubes. Factors to consider could be:

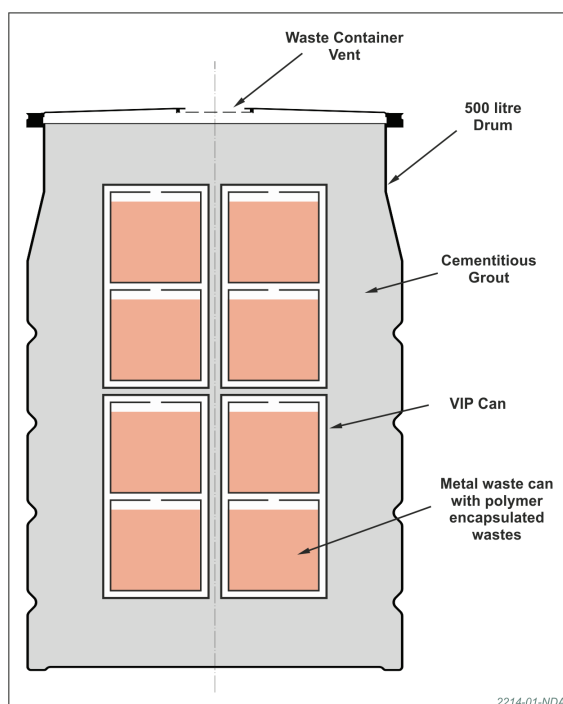
- the reliability of each barrier as manufactured;
- evolution of the barrier and the time period for which reliability could be guaranteed;
- the ability to disperse other gases due to waste degradation whilst maintaining adequate containment of radon; and

- interactions between barriers in the wasteform.

An encapsulation strategy involving the use of multiple barriers has been devised for the packaging of an ILW waste stream containing a significant radium-226 inventory (5C30, see Appendix A) [19]. The strategy (Figure 1) involves polymer encapsulation of the radium bearing waste within vented thin walled (i.e. ~1mm) stainless steel waste cans. The waste cans would be placed within a 500 litre drum, possibly within an outer stainless steel can. Prior to transport to the GDF it is planned to backfill the 500 litre drums with cementitious grout.

The overall radon emanation coefficient for such an arrangement can be estimated by taking the product of the emanation coefficients of each of the barriers. These would include that due to the nature of the waste itself, the polymer encapsulant and the cementitious grout. The overall radon emanation coefficient of the waste package will be the product of emanation coefficient provided by these three 'barriers'. In the specific case of the packaging proposal for waste stream 5C30 no benefit was claimed from the form of the radium but that provided by a minimum cover of 10mm of polymer and the cementitious grout resulted in an estimated emanation coefficient of  $\sim 8 \times 10^{-5}$  for the waste package. This value was shown to be sufficiently low to ensure that the radon emanation from the proposed waste packages would be within the limits derived in Section 4.

**Figure 1 Multi-layer approach to packaging of radium rich ILW**



Over and above the radon emanation issue such a multi layer encapsulation arrangement raises other issues which would need to be addressed including:

- the interaction of the polymer and the cementitious grouts<sup>11</sup>, and the consequences of this for wasteform integrity and emanation coefficients;
- other evolution effects of the various components of the waste and wasteform, notably the generation of bulk gases by the radiolysis etc. (see Section 6.3); and
- meeting the required waste package external radiation dose rate limit.

<sup>11</sup> Notably the effects of high pH porewater from the cementitious grout on the polymer encapsulant.

## 7 Presentation of arguments

As discussed in Section 2.5 a waste packager will be required to submit proposals for the packaging of a particular waste stream for an assessment of its ability to result in disposable waste packages, by way of the Disposability Assessment Process. Guidance on the general form and contents of such a submission can be found in [11], this section provides guidance on the argument and information that a submission will have to include to justify the effectiveness of the features of the packaging proposal that have been included to ensure the safe management of a waste stream containing a significant quantity of radium.

The main aim of the arguments should be the derivation and justification of a radon emanation coefficient for the waste package design and a demonstration that this would result in a radon emanation from a waste package containing the maximum expected radium inventory of no more than the relevant screening level defined in Table 4. In general this will require emanation coefficients to be defined for the waste itself and for the barrier(s) provided by the conditioning process (see Section 6.4.7). The overall emanation coefficient will then be the product of the individual emanation coefficients for however many barriers are claimed to have benefit.

### 7.1 Release of radon from waste

As discussed above, the retention of radon within the waste material may provide a significantly reduced effective generation rate. Although the potential retardation of radon due to diffusion within solid waste particles can be modelled, the validity of the conclusions is dependent on the validity of the assumed parameters describing the waste. It is, therefore, recommended that any claimed benefit for the retention of radon in the waste should be based on experimental measurements of emanation coefficients and/or information from sources such as that provided and identified in [18]. If the waste cannot be sufficiently characterised to allow the use of an analogue (See Section 5.1) to be justified, an emanation coefficient of unity will have to be assumed.

### 7.2 Migration of radon in wasteforms

A number of different mechanisms for the migration of radon through the packaging may be identified, as follows:

- diffusive migration through the solid raw waste placed into a container;
- diffusive migration through an intimately grouted (i.e. encapsulated) wasteform in the aqueous or gas phases;
- diffusive migration through a grout annulus or capping grout in the aqueous or gas phases;
- advection of a mixture of gases including radon through the wasteform or annulus;
- diffusive migration or advection through cracks or defects in the encapsulating medium.

In each case, the rate of migration may be used to derive a time delay before release from the waste package, and the resulting reduction in the rate of radon release estimated.

All arguments should be presented in an appropriate degree of detail. Suitably simplified or conservative arguments will be acceptable, although the following issues may need to be taken into account:



- Arguments may be based on simplified geometries, often one-dimensional. Where this is the case, the validity of the argument for the actual package should be considered. For example, horizontal migration through the sides of a wasteform may represent a shorter path length than vertical migration.
- Factors such as gas compressibility may be neglected in simplified but conservative arguments. However, if such arguments are not sufficient to demonstrate compliance with release limits, more complete descriptions may be appropriate.
- The potentially significant 'transient' period prior to the establishment of a constant pressure and uniform flow may not be included in a conservative argument. However, this period may encompass the entire storage period and hence may be beneficially included in a more complete description.
- The available data for use in the calculations are limited and may need to be validated for a particular system. The relevance of existing literature is always subject to question.
- Models often assume that the barriers presented by the packaging are intact and their properties can be represented by a single-valued parameter (although flawed or cracked wasteforms would also be amenable to modelling). This may be an optimistic over-simplification, and the sensitivity of the calculations should be considered.
- The assumptions upon which arguments are based may change with time. The sensitivity of calculations to such changes should be considered.

In the light of these comments, it is recommended that models should be developed to provide more accurate and realistic representations of the mechanisms.

### **7.3 Evolution of The waste package**

Any argument intended to demonstrate the suitability of a packaging proposal for the mitigation of radon release is required to take due account of the possible evolution of the package during extended storage. Of particular significance are any potential changes to the migration properties of packaging materials and the more general degradation of packaging and of containers intended to contain radon. In addition, if containerisation is adopted, the evolution of the container and its contents should be considered against the requirements of the relevant packaging specifications.

The degree of water saturation in cementitious materials and its evolution may be of particular significance. At high water saturation, the migration of gases can occur only by dissolution of the gas in the pore solution and subsequent diffusion through the barrier. It is relatively straightforward to estimate the rate of radon migration due to such a mechanism. However, arguments based on the barrier presented by saturated cement may be compromised by a number of factors:

- the degree of water saturation may diminish with time as the cement dries and is subject to self-desiccation;
- the generation of bulk gas through, for example, corrosion may cause the wasteform to pressurise, threatening the integrity of the barrier;
- bulk gas pressurisation may also cause two-phase flow or the expulsion of water from the pore structure [20];
- the barrier may crack due to other mechanisms; for example, the expansive corrosion of waste.

Any argument based upon a water-saturated barrier and dissolution-diffusion should consider these possibilities and demonstrate that performance will not be compromised

under the conditions that may be encountered. In practice, it is expected that the development of such an argument will be complicated and difficult to validate.

In addition to the above, the following factors are highlighted as potentially requiring consideration:

- changes in the mass-transport properties of cements as the wasteform evolves;
- degradation of any gas-tight metal containers due to corrosion or pressurisation;
- degradation of any engineered features of containers which act as barriers or limit the rate of radon release (such as the containment boundary and lid seals).

## **7.4 Data for calculations**

Reference [18] provides a review of the availability of published data which demonstrates that the radon migration properties of the various materials encompass a range. Consequently, the use of a particular value of a parameter selected from the literature needs careful justification. It is, therefore, recommended that a case based on modelling should endeavour to use data for the specific materials to be used in the proposed packaging approach. It is possible that this will require additional experimental measurements, specific to the proposal, depending on the degree of confidence required.

## **7.5 Validation of arguments**

### **7.5.1 Validation of radium inventories**

Any case simply based on limitation of the radium-226 inventory to place an upper bound on potential radon releases should be validated using data records of a suitable quality, supported by measurements of radium inventory where practicable. It is noted that significant uncertainties currently exist regarding the radium-226 inventories of many waste streams, and that large variations can occur within those waste streams with high radium-226 inventories.

### **7.5.2 Validation of calculated release rates**

Calculated rates of radon release from packaged wastes should be validated by experimental measurement wherever possible. This is particularly the case where a large reduction in the rate of radon release is being claimed. It is noted that the combination of modelling and experiments also provides a means for extrapolating the measured performance to take account of the evolution of the packaging.

The simple measurement of the rate of radon release from packaged waste potentially provides an unequivocal demonstration that the required reduction in the release rate is achievable. However, guidance on radon measurement methods is not provided herein. An approach based solely on measurement after packaging has a number of potential drawbacks. Firstly, the use of a measurement on the packaged waste carries the risk that, in the event that the packaging is not well designed, the limit will not be met and expensive re-packaging may be required. Secondly, consideration of the evolution of the packaging will be required, perhaps leading to repeated measurements. It should also be noted that, as part of the pre-transport checks required for waste packages, confirmatory measurements will be necessary immediately prior to transport.

## 8 Summary

The release of radioactive gases from waste packages needs to be defined and may need to be controlled to enable compliance with the safety cases for transport and disposal to be demonstrated. Radon is one of a number of radioactive gases; however the generation of radon presents particular concerns due to its mobility and radio-toxicity. Fortunately, the relatively short half-life of the dominant isotope (radon-222 from the decay of radium-226) means that its generation is amenable to mitigation through appropriate packaging. In particular, the rate of radon release can be reduced by radioactive decay during migration through the barriers presented by the packaging.

Analysis of data from the 2010 UKRWI shows that whilst the majority of the radium-226 in wastes destined for the GDF will be concentrated in a relatively small number of waste packages, the packaging of a significant number of other waste streams could result in waste packages with the potential to release radon in quantities that could have a significance for safety during their transport to and/or disposal in a GDF.

Calculations based on pessimistic assumptions, notably that waste packages provide no mitigation of radon release, have been undertaken to derive screening levels for the radium-226 inventory of ILW waste packages. Waste packages with inventories below these screening levels would not raise safety concerns during their transport or following disposal. However, in order to ensure that radon release rates and consequent doses are ALARP, good practice should still be followed in the design of such waste packages.

Proposed waste packages with radium-226 inventories that exceed the screening levels will require specific consideration of this aspect of their performance as part of their disposability assessment by RWM. This guidance provides advice on the measures that could be taken during waste packaging to optimise the mitigation of radon release from such packages. These measures include appropriate sorting and segregation of wastes prior to their conditioning, and the introduction into the waste packages of barriers to radon release. Multi-barrier approaches to waste package design, which progressively reduce radon migration through each barrier without being vulnerable to the failure of a single barrier, could provide a high degree of confidence in radon retention for long-term waste management.

This guidance also provides advice on the presentation of robust arguments to RWM, as part of a packaging proposal, regarding the performance of waste packages with respect to radon release and mitigation thereof. All such arguments should be presented with an appropriate degree of detail, and/or with suitably simplified or conservative arguments, and should take due account of the possible evolution of the waste package during extended storage. Arguments may be based on experimental measurements (e.g. emanation coefficients of raw wastes) and/or models of radon migration in waste packages, although calculated rates of radon release from packaged wastes should be validated by experimental measurement wherever possible.

In summary this guidance provides information to assist with the design of waste packages and the presentation of robust arguments regarding the performance of packaging, in order to facilitate the safe and efficient packaging of radium bearing wastes. However, due to the wide variety of forms of wastes and potential packaging methods, waste packagers are encouraged to discuss their detailed waste packaging plans with RWM at an early stage, in order to obtain independent advice on particular packaging proposals. RWM is prepared to give advice on specific applications, based on its knowledge of waste package behaviour and performance requirements during transport and the operational and post closure periods of a GDF, and from its experience obtained during the research and development of transport and disposal systems.

**Appendix A Information on waste streams with the highest radium inventories in the 2013 UKRWI**

Waste Stream ID	Waste stream description	Projected conditioned waste volume (m <sup>3</sup> )	Mean radium-226 concentration (TBqm <sup>-3</sup> )
5G04	Miscellaneous ILW	6.0E-02	1.14E+00
1A10	ILW Containing Radium	1.1E+01	6.90E-01
6C32	NDS Remote Handled ILW	3.7E-01	1.70E-01
5C30	Harwell Remote Handled ILW	1.2E+02	3.99E-03
5C18/C	Encapsulated ILW Liquors	2.1E+01	6.57E-04
9D22	Sludge	2.3E+01	3.90E-04
5G10	ILW Concrete-lined Drums	1.1E+01	2.54E-04
5C320/C	Encapsulated ILW Sludges	6.5E+00	2.26E-04
5C317	Harwell Contact Handled ILW Drums	9.2E+02	1.77E-04
5C08	ILW Concrete Lined Drums	1.1E+03	1.12E-04
2N01	Drummed Plutonium Contaminated Material	3.4E+01	3.33E-05
5C304	Radiochemical Laboratory Decommissioning CHILW	9.8E+01	1.55E-05
9F38	PWTP Filters - Sand and Gravel	1.1E+01	8.15E-06
5C52	Processed RHILW	1.8E+02	7.68E-06
5C54	Zenith Fuel	7.0E-01	5.19E-06
2F10/C	Encapsulated Centrifuge Cake	6.1E+02	4.97E-06
2F06/C	Encapsulated Barium Carbonate Slurry/MEB Crud	5.3E+02	1.22E-06
2D45	Magnox Fuel End Crops	3.6E+01	6.90E-07
7A29	Uranium Contaminated Operations ILW	3.3E+00	3.79E-07
7A13	Sea Disposal Packs	4.8E+02	1.55E-07

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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 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 [7].

### *bulk gases*

Inactive gases generated within wastes due to chemical processes, such as corrosion, and radiolysis. Commonly dominated by hydrogen.

### *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.

### *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.

### *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).

### *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'.

*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.

*mitigation (of radon release)*

The reduction in the observed or expected rate of radon release from a waste package, or other containment, when compared with the rate of radon generation or the effective generation rate. Mitigation arises from decay of radon during migration through the barriers provided by the waste package.

*Nuclear Decommissioning Authority (NDA)*

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

*Office for Nuclear Regulation (ONR)*

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

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

*permeability*

The property of a permeable material that characterises advective migration. In the Darcy equation, relates the volumetric flow rate of a fluid and the applied pressure gradient.

*permeation coefficient*

A poorly-defined parameter used to characterise the diffusive flux of radon through a solid. May be applied to the product of the radon diffusion coefficient and solubility coefficient (1) (units of  $\text{m}^2/\text{s}$ ), or the product of the radon diffusion coefficient and solubility coefficient (2) or Henry's law coefficient (units of  $\text{mol m}/\text{N/s}$ ). To be distinguished from the permeability.



### *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-2 of this organisation can then be opened up to competition, in due course, in line with other NDA sites

#### *(rate of) radon release*

The net rate at which radon is released to the external environment from an engineered system such as a waste package. The product of the rate of radon generation and the mitigation offered by the packaging, allowing for any retention in the waste itself.

#### *(rate of) radon generation*

The rate at which radon is generated by the decay of radium-226. Equal to the activity of radium-226 if secular equilibrium is achieved.

#### *safety function*

A specific purpose that must be accomplished for safety.

#### *secular equilibrium*

The equilibrium ultimately achieved between a radioactive isotope and its direct progeny isotope(s), at which point the activity of parent and progeny isotope(s) will be equal (for cases where the parent has a longer half-life than the progeny isotope). Achievement of secular equilibrium is approached after a period equal to several half-lives of the progeny isotope.

#### *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.

#### *thoron*

The isotope radon-220, a product of the thorium-232 decay series and the direct progeny of radium-224.

#### *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 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.

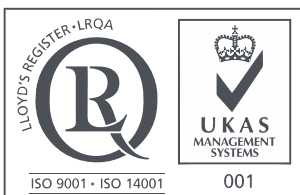
*waste package*

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.





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