

**WASTE PACKAGE SPECIFICATION AND  
GUIDANCE DOCUMENTATION**

**WPS/906: Guidance on the Packaging  
of Closed Sources**

**February 2009  
Number: 10157950**



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**WASTE PACKAGE SPECIFICATION AND GUIDANCE DOCUMENTATION**  
**GUIDANCE ON THE PACKAGING OF CLOSED SOURCES**

This document forms part of a suite of documents prepared and issued by the Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority (NDA).

The Waste Package Specification and Guidance Documentation (WPSGD) provide specifications and guidance for waste packages, containing Intermediate Level Waste and certain Low Level Wastes, which meet the transport and disposability requirements of geological disposal in the UK. They are based on, and are compatible with, the Generic Waste Package Specification (GWPS).

The WPSGD are intended to provide a 'user-level' interpretation of the GWPS to assist Site License Companies (SLCs) in the early development of plans and strategies for the management of radioactive wastes. To aid in the interpretation of the criteria defined by the WPSGD, and in their application to proposals for the packaging of wastes, SLCs are advised to contact RWMD at an early stage.

The WPSGD will be subject to periodic enhancement and revision. SLCs are therefore advised to contact RWMD to confirm that they are in possession of the latest version of any documentation used.

This document has been compiled on the basis of information obtained by the NDA. The document was verified in accordance with arrangements established by the NDA that meet the requirements of ISO 9001. The document has been fully verified and approved for publication by the NDA.



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## 1 INTRODUCTION

The Radioactive Waste Management Directorate (RWMD) of the Nuclear Decommissioning Authority (NDA) has been established with the remit to implement the geological disposal option for the UK's higher activity radioactive wastes. The NDA is currently working with Government and stakeholders through the Managing Radioactive Waste Safely (MRWS) consultation process to plan the development of a Geological Disposal Facility (GDF).

As the ultimate receiver of wastes, RWMD, acting as GDF implementer and future operator, has established packaging standards and defined waste package specifications to enable the nuclear industry to condition radioactive wastes in a form that will be compatible with future transport and disposal.

The primary document which defines the packaging standards and specifications for Intermediate Level Waste (ILW), and certain Low Level Wastes (LLW) not suitable for disposal in other LLW facilities, is the Generic Waste Package Specification (GWPS) [1]. The GWPS is supported by the Waste Package Specification and Guidance Documentation (WPSGD) which comprises a suite of documentation primarily aimed at waste packagers, its intention being to present the generic packaging standards and specifications at the user level. The WPSGD also includes explanatory material and guidance that users will find helpful when it comes to application of the specifications 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 Waste Package Specification and Guidance Documentation, WPS/100*<sup>1</sup>.

The diverse physical, chemical and radiological nature of ILW in the UK means that particular challenges arise in the packaging of certain wastes. To assist waste packagers with the preparation of proposals for the packaging of such challenging wastes, the RWMD has produced, and continues to add to, a suite of thematic Guidance Notes. A full list of the Guidance Notes produced by the RWMD, together with an abstract of each, can be found in *Introduction to the RWMD Waste Packaging Guidance Notes, WPS/900*.

'Closed' or 'sealed' sources containing radioactive materials intended for a variety of industrial and medical uses, present a particular packaging challenge by virtue of their relatively large radionuclide inventory and/or particular features of their construction. This guidance has been produced to assist waste packagers in identifying the challenges presented by the need to package such sources and to identify what treatment processes are available and suitable for the range of sources that exist in the UK.

This guidance should be read in conjunction with the GWPS to which extensive reference is made.

## 2 BACKGROUND

### 2.1 Aims of this Guidance

Spent closed sources are a particular type of radioactive waste for which the packaging for long-term management and disposal may need to address particular issues due to some of their unique characteristics. They may contain activity in concentrations that are

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<sup>1</sup> Specific references to individual documents within the WPSGD are made in this document in italic script, followed by the relevant WPS number.

not often found in more typical ILW. In addition their physical form, or the materials used for their construction, may be such that the techniques generally used for the packaging of ILW may not result in waste packages that would satisfy the needs for passive safety and disposability.

Whilst it is not anticipated that all closed sources will need special consideration it is important that those sources that have the potential to present problems during packaging and their subsequent management are identified at an early stage and that proportionate means are identified for their treatment.

The general aim of this guidance is therefore to assist waste packagers in the identification of the properties of closed sources which could result in them requiring special treatment during packaging and to suggest strategies that would result in waste packages with the required characteristics. The particular aims of this guidance are therefore to:

- identify the properties of closed sources that could result in a need for the use of particular packaging strategies;
- describe the strategies that could be used for the packaging of closed sources with such properties; and
- summarise the strategies that have been used in the UK and internationally for the packaging of closed sources.

The remainder of this section provides summaries of the RWMD's current reference concept for the geological disposal of ILW, the RWMD approach to setting standards and specifications for the waste packages which form the basis for the Letter of Compliance (LoC) process for the assessment of proposals for the packaging of ILW and a brief description of the LoC process<sup>2</sup> itself.

## **2.2 The Concept of Geological Disposal**

A key aspect in the production of standards and specifications for packaged waste is the definition of a disposal system which encompasses all stages of the long-term management of waste from retrieval through to final disposal.

In line with the MRWS consultation process, RWMD are continuing to develop concepts for the geological disposal for higher activity wastes which include ILW, and certain LLW not suitable for disposal in other LLW facilities. It is envisaged that the long-term management of such wastes would comprise a number of distinct stages including:

- the retrieval and conditioning of the waste to create disposable waste packages, usually at the site of waste arising;
- a period of interim surface storage, also at the site of arising;
- transport of the waste packages to a GDF;
- transfer of waste packages underground and emplacement in disposal vaults;
- a period of monitored storage underground, during which retrieval by relatively simple means would be feasible;
- back-filling of the disposal vaults, followed by eventual sealing and closure.

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<sup>2</sup> A full description of the LoC process can be found in *WPS/650*.

The 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.

The Phased Geological Repository Concept (PGRC) [2], has been developed as one manifestation of geological disposal and has been adopted by the RWMD as a reference concept for the purposes of establishing packaging standards. The PGRC is supported by a suite of safety, security and environmental assessments intended to demonstrate that this concept will provide safety to workers and the public and provide the necessary level of environmental protection.

The safety philosophy adopted in the PGRC is one of containment of radionuclides by multiple barriers. Included in these barriers are those provided by the waste package, which itself can be considered as two independent but complimentary barriers, the waste container and the wastefrom, each of which plays an important role in the containment of radionuclides.

As the MRWS consultation process continues it is anticipated that the siting process, based on expressions of interest from volunteer communities, may lead to the identification of one or more sites for investigation as to suitability to host a GDF. The disposal concept design and safety case will be developed to suit the specific characteristics of the site(s) and packaging standards will be updated to reflect the new circumstances as appropriate.

### **2.3 The Generic Waste Package Specification**

A major area of the RWMD's work is the provision of advice to the packagers of radioactive waste in the UK, by way of the definition of packaging standards and the assessment of individual waste packaging proposals against those standards.

The primary document that defines packaging standards for ILW is the GWPS [1]. Derived from the PGRC and its associated generic documentation, which comprise the system specifications and safety assessments that define the PGRC, the GWPS provides the basis for assessing the suitability of waste packages containing ILW for disposal in a GDF.

The packaging standards defined by the GWPS are generic in two respects in that they are:

- derived from a full consideration of all future stage of long-term waste management; and
- independent of the location of the site of a GDF, which could be implemented at a range of different sites within the UK, representing a range of geological environments.

The format of the GWPS is to define:

- general requirements that are applicable to all waste packages;
- a range of standard waste containers;
- specific requirements for the standard waste package designs that are created using the standard waste containers;
- requirements for the conditioned wastefroms that are placed into containers;

- requirements for quality management and for the creation and maintenance of records about each individual waste package.

The GWPS therefore defines the performance requirements for the two barriers to the release of radionuclides provided by the waste package, the waste container and the wasteform, against which the overall performance of waste packages can be assessed.

## **2.4 The Assessment of Packaging Proposals**

Since the mid-1980s, waste producers in the UK have made significant investment in waste retrieval and packaging plant as a means of ensuring that stored 'raw' wastes are rendered passively safe and suitable for disposal. Historically Nirex was responsible for the assessment and endorsement of the suitability of packaging processes for this latter need, originally by way of the 'Letter of Comfort' assessment process. Over the ensuing two decades the Letter of Comfort process has developed and matured to a point that the assessments undertaken were established on a more structured footing with detailed advice being issued to waste producers highlighting further information needs, or need for further development and/or research before a Letter of Comfort could be issued. The assessment process was also modified to integrate better with the implementation of packaging plant projects, with staged interactions occurring at a number of stages before active operation of a packaging plant commenced. The status of the assessment process was strengthened in January 2004, when support was provided by UK nuclear regulators, and it was recognised within improved regulatory arrangements for nuclear licensed sites [3]. This was accompanied by significant changes to the assessment process which was renamed the 'Letter of Compliance' assessment process, a full description of which can be found in *Guide to the Letter of Compliance Assessment Process, WPS/650*.

In April 2007 Nirex was dissolved and its responsibilities assumed by RWMD. This included the role of assessing and endorsing nuclear site operators' waste packaging proposals through the LoC assessment process.

In undertaking LoC assessments RWMD determines whether wastes, when packaged, will have characteristics compliant with plans for transport to, and operations at a GDF, and ultimately whether the wastes could be accommodated within a GDF long-term post-closure safety case. The main output of a LoC assessment is an Assessment Report which may be accompanied by the issue of a LoC endorsing the packaging proposal. In line with the recently updated regulatory guidance [4] such endorsement is now seen by the regulators as an important component of the operator's Radioactive Waste Management Case.

## **3 TYPES AND USES OF CLOSED SOURCES**

### **3.1 Definition of closed source types**

For the purposes of this Guidance, the term 'closed source' is used to mean any discrete item manufactured with the intention of producing specific emissions through the radioactive decay of a particular radionuclide. Such a definition will include a number of different physical arrangements including homogeneous, laminated and sealed sources.

The use and disposal of closed sources in the UK is regulated by the relevant environmental body (for example, Environment Agency (EA) for England and Wales), who monitor compliance with the Radioactive Substances Act 1993 (RSA) [5]. Under the RSA, users of closed sources are generally required to hold a Registration, although there are a number of exceptions to this, usually due to the low activity of the source. For

instance, the Radioactive Substances (Testing Instruments) Exemption Order SI1049 (1985) [6] allows sources with activities up to 4MBq<sup>3</sup> to be held without registration.

Under another Exemption Order, The Radioactive Substances (Waste Closed Sources) Exemption Order S.I.1831 (1963) [7], users of closed sources do not need to have an Authorisation for disposal of radioactive waste. This Exemption Order also provides a legal definition of a closed source, as a '*homogeneous source, a laminated source or a sealed source*'.

Reference [7] also includes definitions for each of these three main types of closed sources, which can be summarised:

**Homogeneous Source:** '*An article, free from patent defect which is made wholly from a substance which is solid, coherent, homogeneous and tough and is radioactive material ... or incorporates radioactive material*'.

This type of source includes a wide range of forms ranging from metal and alloy wires to epoxy resin blocks cast to contain the radionuclide. Because of this wide range of forms, each type of source construction and source radionuclide may require separate consideration in terms of its packaging requirements. However, in general the radionuclide content of this type of source is lower than other types of sealed source and disposal routes, other than to a GDF, may be more applicable.

The robustness of such sources will depend on the exact method of manufacture. For example, the most common examples of homogenous sources in current use are radiography sources containing Ir-192, which are manufactured from neutron irradiated iridium wire. As such, these sources are expected to be relatively robust to damage and small users occasionally prepare them for disposal by mixing them with an epoxy resin binder.

Depleted uranium shielding, such as that used in radiography or teletherapy equipment is often also interpreted as a 'homogeneous source'.

**Laminated Source:** '*An article free from patent defect consisting of a layer of radioactive material sandwiched between and bonded to layers of coherent, inert and tough material*'.

Common examples of this type of source are those used in smoke detectors (containing Am-241) and lightning preventors (Ra-226). These radionuclides are typically laminated between two layers of a metal such as gold or silver, a form of construction that is not always physically robust and which may be prone to damage and leakage of its radioactive contents. In general, the radionuclide content of this class of sources is also relatively low, particularly when compared with 'sealed sources'.

**Sealed Source:** '*Radioactive material sealed in a container or bonded wholly within material, the immediate container or the bonding being of adequate mechanical strength and free from patent defect*'

Sealed sources, as the name implies, are sources of radionuclides that are encapsulated within a robust container or capsule, often made of welded metal containers, usually stainless steel or titanium. Higher activity sealed sources may be doubly encapsulated, such robust construction being reserved for sources with higher penetrating radiations

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<sup>3</sup> This value is higher for certain isotopes (e.g. for Ni-63 the limit is 600MBq).

(e.g.  $\gamma$ -radiation and neutrons). The majority of the radionuclides in sealed sources are themselves in a robust form within the capsule; typically as metals, ceramics or salts pressed into pellets.

This class of source generally contains the highest inventories of radionuclides. However, because of the robust construction of the enclosing capsule and of the radionuclides they contain, sealed sources can provide a high degree of containment and resistance to dispersal of their contents.

There are many designs of sealed source in use; for example, Cs-137 medical sources and Am-241/Be neutron sources, and a wide range of radionuclide inventories for each design.

The term 'sealed source' is often used colloquially, in place of 'closed source', and whilst this guidance considers all forms of closed source, it is recognised that sealed sources tend to have the highest specific activities and hence may require the greatest consideration in relation to waste package design and performance.

It is also noted that there are a number of source designs that do not comply with the definitions given above, the so-called 'open sources'.

Each source type has requirements imposed on their physical form, fitness for purpose and leak rate. These requirements are, however, set in the context of their correct use and management. For example, alpha sources typically contain less than  $4 \times 10^4$  Bq but can have greater activity when used by competent personnel in laboratory applications. Very low energy decay mode radionuclide sources are even prepared by simple plating onto a suitable substrate; forming open sources. This may be covered with a thin electroplated layer. Although the radionuclide inventory is usually small, the radionuclides are not considered as fixed or immobilised by the source construction.

The Exemption Order does not specify a maximum leakage of radionuclides from closed sources. For sealed sources, this is provided by British Standard 5288:1976 [8], and other related international standards.

The Ionising Radiations Regulations (Regulation 18) [9] require that closed sources be leak tested by an approved method at intervals of not more than 26 Februarys when in use. Closed Sources may be regarded as Special Form Radioactive Material under the IAEA Transport Regulations [10] when manufactured, taking credit for the degree of containment that they can be shown to provide.

### **3.2 Examples and uses of closed sources**

There is a wide range of applications for closed sources. The main types and uses of the closed sources that are likely to be encountered in ILW management are:

- Nuclear borehole logging; by gamma ray back-scattering (usually Cs-137) and neutron back-scattering (usually Am-241/Be). These are sealed sources.
- Process control instrumentation; using beta or gamma transmission or back-scattering, X-ray Fluorescence (XRF) or neutron backscattering. The range of radionuclides and specific activities employed is very wide.
- Industrial radiography; Co-60, a sealed source, and Ir-192, a homogeneous source. Radiography equipment often includes depleted uranium shielding, which, for regulatory purposes, is normally also treated as a homogeneous source.

- Alarms; Am-241 and occasionally Ra-226 laminated sources and tritium or Ni-63 electron capture detectors which are open sources. Although not strictly closed sources, open sources are managed as ILW under the Testing Instruments Exemption Order in a manner analogous to closed sources.
- Radiation processing; Co-60 sealed sources used in sterilisation processes.
- Static elimination; Po-210 and, historically, laminated foils containing Ra-226 and Am-241
- Heat and light sources; light from phosphors activated by tritium, heat from Pu-238 decay in a sealed source
- Analytical measurements; these may employ a wide range of source types, including Fe-55, Cd-109, Am-241 and Co-57
- External beam therapy; including Co-60, Sr-90 and Cs-137 sealed sources.

The likely range of specific activities of each radionuclide source type and main applications are summarised in Appendix A.

There has been a general trend since at least the 1980s towards non-radioactive techniques which have largely or completely replaced closed sources. Despite this, there are a significant number of applications for which closed sources remain the only or most suitable option, as well as a significant stockpile of sources manufactured since the 1950s and now in storage awaiting conditioning for disposal.

#### **4 POTENTIAL ISSUES RAISED BY THE PACKAGING OF CLOSED SOURCES**

As outlined in Section 2.4, part of the purpose of the LoC assessment process is to ensure that waste packages will be compliant with the requirements of the GWPS and thereby with the needs of transport to and emplacement in a GDF. Accordingly, the issues raised by the packaging of closed sources will need to be addressed as part of the LoC assessment of a packaging proposal. From a consideration of the range of physical nature and radionuclide inventory of closed sources described in Section 3, it is apparent that closed sources will have particular implications for certain areas of wastefrom and waste package performance.

A review of the performance criteria in the GWPS suggests that the requirements specified for a number of wastefrom and waste package properties and performance criteria could be made difficult to achieve by the presence of closed sources, specifically:

- Wastefrom:
  - Immobilisation;
  - Hazardous materials;
  - Voidage;
  - Homogeneity;
  - Mechanical and physical properties;
  - Radioactive gas release.
- Waste package:
  - External dose rate
  - Heat Generation

- Criticality safety
- Impact and fire accident performance.

This Section considers how the presence of closed sources could give rise to issues that would make the demonstration of compliance with each of these criteria more challenging and gives guidance as to when particular attention should be given specific measures will be required when devising packaging plans. This Section also identifies high level approaches that could be adopted to mitigate the effects of the presence of closed sources; more detail on each of these strategies is provided in Section 5.

## **4.1 Wasteform properties and performance**

### **4.1.1 Immobilisation**

The GWPS requires that *'All reasonable measures shall be taken to ensure that radionuclides and toxic materials in the waste are immobilised and that loose particulate material is minimised'*. This requirement aims to ensure that releases of radionuclides and toxic materials are minimised during the normal and accident conditions that may arise during all stages of the long-term waste management of waste packages from manufacture to backfilling of the GDF vaults.

Particulates may be present in some designs of closed source, and there is also the potential for degradation of the source to generate particulates. Such particulates represent a source of potentially mobile radioactivity that could be released from the waste package, particularly following an impact accident if the waste container was breached.

The corrosion of 'reactive metals' (e.g. homogeneous sources comprising depleted uranium, or with aluminium containment around closed sources) may generate a mobile particulate source term or, in extreme cases, threaten the integrity of the wasteform through the formation of expansive corrosion products or the generation of gas. This issue is not specific to closed sources, although it may be relevant if reactive metals are present, and is therefore not considered further in this report.

Free liquids also represent a potentially mobile source of hazardous and radioactive materials. The GWPS requires that *'All reasonable measures should be taken to exclude free liquids from the wasteform... Free liquids not removed from wastes prior to waste packaging should be immobilised by a suitable waste conditioning process'*. Closed sources containing free liquids are unusual but when present should be removed or solidified wherever practicable.

*Guidance on the Immobilisation of Radionuclides in Wasteforms, WPS/903* quantifies the minimum quantity of mobile particulate activity that may be considered significant in the context of the long-term management of waste packages. This concluded that no specific measures or conditioning processes would be required to ensure the immobilisation of particulates where their radionuclide inventory is less than:

- $1.5A_2^4$  in a 500 litre Drum waste package;
- $4A_2$  in a 3 cubic metre Box waste package; or
- $6A_2$  in a 3 cubic metre Drum waste package.

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<sup>4</sup>  $A_2$  is a measure of activity linked to possible exposure pathways defined in the IAEA Transport Regulations [10].



Accordingly, if the total activity in potentially mobile form within a waste package is less than these quantities, no specific measures will be necessary to ensure the immobilisation of such activity. In other cases, it will be necessary to make a case that the proposed wastefrom will provide adequate immobilisation (see Section 5.3).

It is generally desirable for source materials to be present in an insoluble form whenever possible. However, in some cases, and particularly for older sources [11], the radionuclide(s) present may be in a soluble form that may need to be further considered in terms of Best Practicable Means (BPM) for the containment of radionuclides; for example, Cs-137 may be present as soluble chloride or sulphate. The use of a waste container that will maintain their integrity for a period of 500 years (as required by the GWPS) is expected to provide adequate containment in most cases, so that additional measures for containment of short-lived soluble radionuclides will not be required in most cases.

Gaseous radionuclides, or gases labelled with radionuclides also represent a potentially mobile source of activity. The potential for the release of radionuclides present as gases is considered in Section 4.1.6.

#### **4.1.2 Hazardous Materials**

The GWPS lists a number of materials that are considered hazardous if present in significant quantities in wastefroms. Specifically these include flammable, explosive, pyrophoric, chemo-toxic and oxidising materials as well as sealed and/or pressurised containers; and materials or objects containing stored energy. Such materials are specifically prohibited from wastefroms unless their conditioning renders them safe.

Many closed sources are by their nature 'sealed containers' that may have become pressurised since manufacture and a number of the prescribed hazardous materials are also present in some of the closed sources listed in Appendix A.

The chemical form of some source materials may render them hazardous because of their toxicity or reactivity. It may be necessary to demonstrate that these hazards will be adequately controlled, either by removal of the hazard or by preventing their release.

Strategies that may be used to mitigate threats posed by hazardous materials can be summarised as:

- Removal of the hazard (see Section 5.4)
- Isolation of hazardous materials (see Section 5.3).

Two specific types of hazardous material that may be present in closed sources are discussed below.

Beryllium is a toxic material of significance to the performance of a GDF and is used for 'windows' in some closed sources as well as being an integral part of some neutron sources.

When present in neutron sources, the beryllium will be intimately mixed with the other radionuclide (e.g. Ra-226, Am-241), so that separation and exclusion of the beryllium will not be practicable. The removal of thin beryllium windows from closed sources incorporating them is unlikely to yield sufficient benefit in terms of the overall toxicity potential of a GDF to justify the attendant operator dose uptake. In cases where beryllium is present, but cannot reasonably be excluded, the inventory and form of beryllium should be reported in the packaging proposal as accurately as is possible to permit assessment of the hazard. This will apply as much to sources as to other wastes.

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The presence of sealed containers within a wasteform is undesirable as the generation of gas within them may result in over-pressurisation and rupture. Such failure could result in the dispersal of its contents and disruption of other components of the wasteform and waste package. This is a particular potential hazard for closed alpha sources (for example those containing Ra-226 or Am-241) as a result of the helium gas generated. Estimation of the scale of the extent of helium pressurisation can be achieved from a knowledge of:

- the initial radionuclide inventory of the source;
- the fraction of helium atoms which may remain trapped in the matrix of the source materials, and;
- the internal volume of the source that is available for the gas to occupy.

Box 1 provides an example of such a calculation for a large Am-241/Be neutron source.

**Box 1 Gas pressure calculation for Am-241/Be neutron source**

Source Inventory: 925GBq Am-241 (Half life = 432 years)  
No. of decays in 150 years =  $3.9 \times 10^{21}$  = 0.007 moles of He  
No. of decays in 500 years =  $1.0 \times 10^{22}$  = 0.017 moles of He  
Assuming a voidage of  $10^{-5} \text{ m}^3$  (10% of total internal volume of source\*)  
and a source temperature of 300K:  
Pressure after 150 years = 1.6MPa  
Pressure after 500 years = 4.2MPa  
\* The total volume within the inner encapsulation of the AMN-26 source is  $\sim 100 \text{ cm}^3$ , most of which is occupied by a compacted mixture of americium oxide and beryllium metal [12].

Pressures of the magnitude shown in Box 1 may contribute to failure of the source enclosure, rendering the radioactive contents more susceptible to release, although the pressure required to cause failure will depend on the manufacturing specification and the condition of the source.

On heating, closed sources that contain gases will undergo increased pressurisation which may be of relevance under normal conditions for wasteforms with a significant radiogenic heat output, and under fire accident conditions.

**4.1.3 Voidage**

Closed sources may contain small volumes of voidage. According to the GWPS, '*All reasonable measures shall be taken to ensure that the volume of voidage within the waste package (such as ullage space and other holes or spaces) is minimised*'. The presence of voidage can reduce the predictability of wasteform performance and evolution, so that its minimisation is considered best practice.

For packaging proposals that involve the encapsulation of discrete solid items such as closed sources, it should be demonstrated that the chosen encapsulant has sufficient fluidity to penetrate interstices between items. Closed sources are typically physically small, of the order of a few tens of millimetres, and when loose-tipped into a waste container may be difficult to infiltrate.

Benefit may be gained from the presence of an intact capsule around the source material and this can outweigh any benefit to be gained from the removal of a small quantity of voidage. Accordingly, it is not recommended that sources be routinely opened to allow infiltration of voidage.

#### 4.1.4 Homogeneity

It is a requirement of the GWPS that '*Local concentrations of materials within the wasteform that may compromise the ability of the waste package to meet any aspect of this Specification should be avoided*'. Closed sources are generally physically small, being only of the order of a few tens of millimetres in size and this will result in localised concentrations of activity and of the associated source of internal and external dose, radiogenic heat, and potentially mobile radionuclides. If conditioned without adequate attention they will therefore result in a wasteform which is inhomogeneous in the distribution of activity, and thereby heat output and radiation dose.

Higher radioactive dose rates and heat outputs may be experienced in the proximity of a source than would be expected for a wasteform with a uniform distribution of the same radionuclide inventory throughout. These may cause the acceleration of chemical and physical processes that may threaten wasteform integrity and other requirements of the GWPS. Local concentrations of radionuclides may also lead to the disproportionate release of radionuclides and excessive external dose rate under both normal and accident conditions. For example:

- Increased temperature may accelerate corrosion of the metal enclosure of a closed source. This may result in earlier loss of the containment provided by the source construction;
- Increased temperature may accelerate the corrosion of other wasteform components (i.e. metals) and increase gas generation within the wasteform. This may result in stressing of the wasteform that may lead to wasteform cracking at an earlier time than expected and the generation of potentially mobile particulates;
- Differential stresses in a wasteform may be caused by heat-generating sources and may result in cracking of the encapsulating matrix;
- Localised high irradiation of the wasteform may lead to accelerated deterioration;
- A local high concentration of gaseous radionuclides (e.g. tritium, Kr-85, Rn-222<sup>5</sup>) from sources may give rise to an unacceptably large release of radionuclides under normal or accident conditions (see Section 4.1.6);
- A local high concentration of mobile radionuclides may give rise to an unacceptably large release of radionuclides under impact and fire accident conditions (see Section 4.2.4);
- A local high concentration of radionuclides emitting penetrating gamma radiation may give rise to unacceptably large external dose rates during transport and could result in a need to repackage the waste (see Section 4.2.1).
- If the packaged waste is to be transported as either Low Specific Activity (LSA) material or Surface Contaminated Objects (SCO), it will need to be demonstrated that the nature of the sources and their packaging is consistent with the requirements of the IAEA Transport Regulations [10] in respect of requirements such as the uniformity of distribution of radionuclides. *Guidance on the Application*

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<sup>5</sup> From sources containing Ra-226.

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*of LSA Material Criteria to Waste Packages, WPS/910 is of relevance in this matter.*

The tolerance of a cementitious wasteform to a temperature gradient across the wasteform is not well defined but is generally thought to be in the order of  $\sim 150^{\circ}\text{Cm}^{-1}$ , above which differential thermal expansion may result in wasteform cracking.

Appendix B illustrates the potential heating effect of a large ( $\sim 80\text{TBq}$ ) Cs-137 gamma source of the type described in [12]. This shows that the potential for large temperature gradients (i.e.  $>1000^{\circ}\text{Cm}^{-1}$ ) exists in the immediate vicinity of a source generating significant quantities of heat, although this falls rapidly with distance from the source (i.e. by a factor of  $\sim 10$  at 50mm from the source). Wasteform temperatures can be high in the vicinity of such a source (the example shown in Appendix B shows that this could be up to  $\sim 100^{\circ}\text{C}$  immediately adjacent to the source) but this also falls steeply with distance from the source (i.e. to  $<80^{\circ}\text{C}$  at 10mm from the source)

This shows that the potential for thermally accelerated corrosion etc. of the source or wasteform or for cracking of the wasteform due to differential expansion is limited to a relatively small volume.

Irradiation of the wasteform, particularly in the immediate vicinity of a source could lead to accelerated deterioration and cracking of the encapsulating medium. In the case of inorganic cement encapsulated wasteforms, the wasteform is expected to be tolerant to absorbed doses up to the order of 100MGy [13]. Over a 50 year period a source such as that considered in Appendix B would result in an estimated total absorbed dose of approximately 800MGy adjacent to the source. However, as is the case with thermal effects discussed above, the absorbed dose will fall sharply with distance and, as a result a relatively small volume of wasteform, will be subjected to such high doses.

Large Co-60 sources may also generate unacceptably large temperature and radiation fields within a waste package, although, given the relatively short half-life of this radionuclide (i.e.  $\sim 5$  years), moderate periods of decay-storage of the sources are likely to result in radionuclide activity levels within acceptable bounds before they are packaged.

Although most sources have lower radionuclide activity than given in the example above, several sources may be packaged together and, in total, represent a source of significantly greater magnitude. The potential effects of heat and dose from closed sources, particularly closed sources, suggest that great care may be needed if a number of sources were to be packaged together.

Strategies that may be used to mitigate threats posed by a lack of wasteform homogeneity can be summarised as:

- Control of radionuclide inventory (see Section 5.2)
- Control of waste distribution (see Section 5.5).

#### 4.1.5 Radioactive gas release

Closed sources may contain gaseous radionuclides such as Kr-85 and tritium<sup>6</sup>, or generate them as a result of radioactive decay (e.g. Rn-222).

The GWPS sets no limits on the quantities of radioactive gases that may be packaged but rather defines gas generation limits from waste packages following manufacture.

The most bounding limits on radioactive gas release from waste packages are set by the IAEA Transport Regulations [10] for unshielded waste packages transported in a shielded transport container as a Type B transport package under Normal Conditions of Transport (NCT). The values for tritium and all other radioactive gases are reproduced in Table 1 for ease of reference.

**Table 1 Allowable gaseous activity releases for standard unshielded waste packages (in A<sub>2</sub> per day)**

	Activity release limit (A <sub>2</sub> per day)		
	500 litre Drum	3 cubic metre Box	3 cubic metre Drum
Tritium	1.0x10 <sup>-4</sup>	1.9x10 <sup>-4</sup>	3.3x10 <sup>-4</sup>
All other gases	4.3x10 <sup>-4</sup>	7.7x10 <sup>-4</sup>	1.4x10 <sup>-3</sup>

Table 2 shows the equivalent activity release rates in TBq per day for the three gases identified in Appendix A as being likely to be present in closed sources. In the case of Rn-222 this is also given in terms of the quantity of Ra-226 which, if present in a waste package, would result in the generation of the specified quantity of Rn-222.

**Table 2 Allowable gaseous activity releases for standard unshielded waste packages (in TBq per day)**

Gas	Activity release limit (TBq per day)		
	500 litre Drum	3 cubic metre Box	3 cubic metre Drum
Tritium	3.5x10 <sup>-3</sup>	5.2x10 <sup>-3</sup>	1.1x10 <sup>-2</sup>
Kr-85	3.6x10 <sup>-4</sup>	5.2x10 <sup>-4</sup>	1.1x10 <sup>-3</sup>
Rn-222	1.5x10 <sup>-6</sup>	2.1x10 <sup>-6</sup>	4.5x10 <sup>-6</sup>

The gaseous radionuclide Rn-222 is continuously generated as a consequence of alpha decay by sources containing Ra-226. Of relevance here is *Guidance Note on the Packaging of Radon-Generating Wastes, WPS/902* which identifies the quantities of Ra-226 that can be packaged without incorporating specific measures to limit Rn-222

<sup>6</sup> Most sources containing tritium do so in the form of a solid compound (e.g. a metal tritide), from which the release of gaseous tritium is likely to be small. Some sources, such as gaseous tritium lighting devices (GTLTD) will however contain gaseous tritium and may be vulnerable to puncturing.

release to less than the values given in Table 2. On the basis that 1TBq of Ra-226 will generate Rn-222 at a rate of ~0.2TBq/day, 'threshold quantities' can be calculated for the allowable inventories of Ra-226 in the standard unshielded waste packages, and these are listed in Table 3

**Table 3 Threshold quantities of Ra-226 in standard unshielded waste packages**

<b>Waste Package Type</b>	<b>Threshold Quantity of Ra-226 (TBq)</b>
500 litre Drum	$8.3 \times 10^{-6}$
3 cubic metre Box	$1.2 \times 10^{-5}$
3 cubic metre Drum	$2.5 \times 10^{-5}$

When the values in Table 3 are compared with the inventories of typical closed sources containing Ra-226 listed in Appendix A, it can be seen that many exceed these threshold quantities. Accordingly the potential for the release of Rn-222 from such sources will need to be considered in development of packaging plans. Waste packages containing a greater inventory than the threshold quantity will require a justification of the long-term integrity of the sources or specific measures being incorporated in the wasteform or waste package design to retain Rn-222 when released from the sources.

Strategies that may be used to control the rate of radioactive gas release can be summarised as:

- Controlling the inventory of gaseous radionuclides and radionuclides present as gases (see Section 5.2)
- Ensuring that the waste, wasteform and waste container provide an adequate degree of immobilisation (see Section 5.3.2).

#### **4.1.6 Mechanical and physical properties**

The GWPS defines requirements for a number of other wasteform properties not discussed above. These comprise:

- mechanical strength;
- mass-transport properties;
- thermal conductivity, and;
- leachability.

Whilst the presence of closed sources in a properly designed wasteform is unlikely to have a significant effect on any of these properties, attention should still be given to them, notably to mass-transport properties and thermal conductivity, to ensure that the wasteform is designed with the characteristics of the sources in mind.

The GWPS requires that the mass-transport properties of the wasteform are such as to allow gases generated within the wasteform to be released without causing damage to the wasteform whilst also achieving values for diffusivity and permeability that are compatible with providing BPM for the containment of water-soluble radionuclides. The presence of sealed sources within the wasteform may affect wasteform mass-transfer properties, for

example by acting as locations from where cracks could propagate, and result in values for diffusivity and permeability that are not compatible with the assumptions made in the post-closure modelling a GDF.

The effects of heat generation by closed sources have been discussed in Section 4.1.4 where it was concluded that these effects would be limited in severity as well as in the volume of wasteform that could be affected. However, such a conclusion can only be supported for a wasteform with adequate thermal characteristics, particularly thermal conductivity. The GWPS recommends a minimum value of  $0.5\text{W m}^{-1}\text{K}^{-1}$  for wasteforms to ensure adequate thermal characteristics of the wasteform under normal and accident conditions and to ensure thermal compatibility of waste packages with the GDF. Overall waste package thermal conductivity in the range  $0.5\text{-}5\text{W m}^{-1}\text{K}^{-1}$  is deemed to be acceptable and this should be achieved for all waste packages irrespective of contents.

## 4.2 Waste package properties and performance

### 4.2.1 External dose rate

Closed sources are likely to contain a significant inventory of penetrating radiations (i.e. both gamma and neutron radiation) when packaged. The higher activity closed sources can have activities that may be in excess of 1TBq each, for example, radiography sources may contain up to 8TBq of Co-60 or 80TBq of Cs-137 when manufactured. This may lead to high package external dose rates if the sources are not packaged appropriately. The GWPS requires that *'The dose rate at 1 metre from the surface of a transport package shall not exceed  $0.1\text{mSv h}^{-1}$  and the dose rate on its external surface shall not exceed  $2\text{mSv h}^{-1}$ . In the case of unshielded waste packages, the dose rate should not exceed the values given above when the waste package is shielded by a 280mm thick steel shield (density  $7700\text{kg m}^{-3}$ ) in direct contact with the package'*.

The waste, wasteform and container will provide a degree of shielding for the waste within it. For sources containing radionuclides that emit primarily alpha and beta particles, with very small associated gamma emissions, the container alone is likely to provide sufficient shielding to render any associated external dose rate insignificant.

Strategies that may be used to ensure that the external dose rate from waste packages is consistent with the requirements of the GWPS can be summarised as:

- Control of radionuclide inventory (see Section 5.2)
- Control of the location of sources within the waste package, and the uniformity of distribution of the sources within the waste package (see Section 5.5)
- Ensuring that the degree of shielding, and/or neutron attenuation, provided by the waste container and wasteform is sufficient to limit dose rate (see Section 5.6).

### 4.2.2 Heat output

The GWPS sets total heat output limits for waste packages at two key stages in their long term management; during transport and following vault backfilling. For planning purposes the earliest dates for these two stages are assumed to be 2040 and 2090 respectively.

Table 4 lists the maximum heat outputs for unshielded waste packages at these two stages.

Table 5 lists the maximum inventories derived from the 500 litre Drum waste package transport heat output limit of 50W for the radionuclides listed as being used in sources in Appendix A. Also shown is the decay factor for the 50 year period between 2040 and 2090 which indicates which of the limits is bounding, a factor of less than 0.5 indicates that the transport is more bounding.

**Table 4 Heat output limits for unshielded waste packages**

Waste Package Type	Maximum Heat Output (W)	
	During Transport	Following vault Backfilling
500 litre Drum <sup>7*</sup>	50	25
3 cubic metre Box	200	150
3 cubic metre Drum	200	130

**Table 5 Limiting radionuclide inventories for 500 litre Drum waste packages for 50W heat output**

Radionuclide	Inventory to give 50W	50 year Decay factor	Radionuclide	Inventory to give 50W	50 year Decay factor
	(TBq)			(TBq)	
Am-241	55.4	0.92	Kr-85	1235	0.04
Ba-133	685	0.04	Ni-63	18200	0.71
Cd-109	2874	0.00	Pm-147	5060	0.00
Cf-252	17.0	0.00	Po-210	57.7	0.00
Cm-244	52.9	0.15	Pu-238	55.8	1.00
Co-60	120	0.00	Ra-226	11.5	0.98
Cs-137	38.5	0.32	Ru-106	192	0.00
Fe-55	53000	0.00	Sr-90	276	0.31
Gd-153	2150	0.00	Tl-204	260000	0.00
H-3	54700	0.06	Depleted uranium	73	1.00

Comparison of the values in Table 5 with the inventories of typical close sources given in Appendix A shows that, with the possible exception of large Co-60 sources, no single source has an inventory close to the limiting case. In most cases there are differences of many orders of magnitude difference indicating that gross heat output is unlikely to be a bounding factor in the packaging of sources. The thermal consequences of the localised concentration of heat on wastefrom integrity is likely to be more of an issue and is addressed in Section 4.1.4 which deals with the effects of a lack of homogeneity in wastefroms containing closed sources.

<sup>7</sup> The 500 litre Drum is assumed to be carried in a four drum stillage with 3 identical waste packages



A comparison between the values in Table 5 with those for close source inventories shows that, with the exception of very large Co-60 sources used in sterilisation plants, none of the sources, either individually or when in groups of a few 10's, will approach the heat generation limits for the 500 litre Drum waste package.

Whilst total waste package heat output is unlikely to present an issue during the package of sources of the types listed in Appendix A, some issues may arise from the concentration of activity in closed sources and the associated localised heating. This is addressed in Section 4.1.4.

### 4.2.3 Criticality safety

The GWPS states that *'The presence of fissile materials, neutron moderators and reflectors in the waste package shall be controlled to ensure that they do not present a criticality safety hazard during any of the active phases of the PGRC. It shall also be ensured that, following closure of the repository, the possibility of local accumulation of fissile material such as to produce a neutron chain reaction is not a significant concern to long-term repository performance. Shielded waste packages shall, in addition, comply with the requirements of the IAEA Transport Regulations [10] for fissile excepted transport packages'*.

Whilst none of the closed sources listed in Appendix A contain fissile materials<sup>8</sup> the consequences of the presence of such materials, as well as those which may influence neutron chain reactions (e.g. Pu-238 in heart pacemaker batteries and Cf-252 in neutron sources) and/or neutron moderators and reflectors (e.g. beryllium and depleted uranium), must be considered during the development of packaging proposals.

The quantity of such materials associated with sources will need to be quantified and carefully controlled to ensure that the risk of criticality at any stage of their long-term management is reduced to an acceptable level.

The RWMD approach to criticality safety is based on the definition of 'screening levels' for the quantity of fissile material in waste packages, below which the risk of criticality is eliminated or the consequences of such an event not a significant concern. This has led to the definition of a generic screening level of 50g of Pu-239 (or quantity of other fissile material with equivalent reactivity) which can be used to justify the criticality safety of waste packages if it can be demonstrated that the fissile material loading will not exceed this level.

For waste packages containing more fissile material than the generic screening level a package specific Criticality Safety Assessment (CSA) may need to be undertaken, depending on the nature of the fissile material. This would need to take into account the presence of neutron sources and modifiers that could be co-packaged with the fissile material.

Criticality Compliance Assurance Documentation (CCAD) will be required to show how the defined limits on materials relevant to criticality will be achieved in practice. This will include demonstration that the generic screening level will be adhered to or, in cases where a package specific CSA has been produced, that the relevant safe fissile mass is not exceeded. *Guidance on the Preparation of Criticality Compliance Assurance Documentation for Waste Packaging Proposals, WPS/625* is of relevance here.

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<sup>8</sup> 'Fissile materials' are generally assumed to be U-233, U-235, Pu-239 and Pu-241, although certain isotopes of higher actinides (e.g. americium, curium and californium) are also capable of forming critical assemblies.

Justification of waste package acceptability in terms of criticality safety will rely on inventory control (see Section 5.2). The attenuation of neutrons from neutron sources could be achieved using measures described in Section 5.6.

#### **4.2.4 Impact and fire accident performance**

The GWPS defines activity release limits for a range of defined accident conditions involving impacts and fire. The presence of intact closed sources within a properly formulated wasteform should not affect the ability of a waste package to be compliant with these requirements.

The performance of waste packages following impact and fire accidents is dependent on the respective mechanical or thermal properties of the waste container and wasteform under the conditions pertaining during these accidents and activity releases will be a function of these and the radionuclide inventory of the waste package. Whilst closed sources constitute localised concentrations of activity they should not result in inventories which would challenge the ability of waste packages to comply with the GWPS. For impacts and fires resulting from a transport accident activity must escape from the damaged seal of the transport container in order to create a hazard. For GDF accidents the activity must be in a form that will allow dispersal by way of normal ventilation air flows. For either type of accident this requires activity to be in gaseous or fine particulate form (for transport accidents this is defined as  $<40\mu\text{m}$  and for GDF accidents  $<100\mu\text{m}$ ).

As stated in Section 3 the activity in some closed sources is in gaseous or powder form. However, the robust nature of most sources, together with suitable wasteform formulation will ensure that such activity is not released from the source during an impact and/or fire accident.

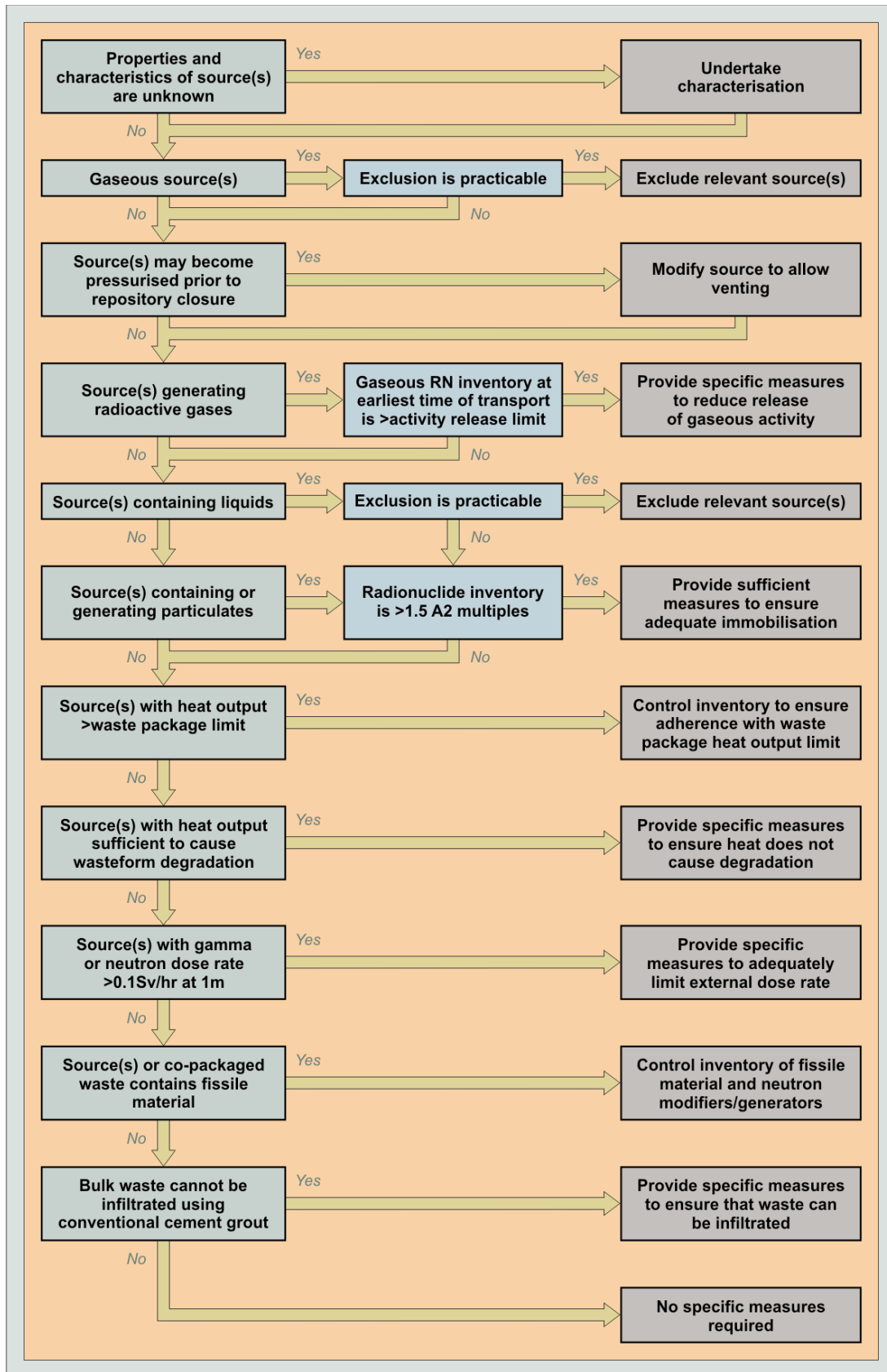
## **5 PACKAGING STRATEGIES FOR WASTES CONTAINING CLOSED SOURCES**

Figure 1 provides a summary of the properties and characteristics of closed sources that may give rise to issues that will make the demonstration of compliance with the requirements of the GWPS more challenging. This illustrates the three principle approaches which could be adopted to the packaging of closed sources. i.e.:

- *exclusion* of closed sources from waste to be packaged;
- *control* of the radionuclide and/or non-nuclear inventory, and/or;
- pre-treatment and/or *conditioning* of the closed sources by a suitable method.

The actual approach adopted will depend on issues to be addressed during the definition of a long-term management of a particular source type. This will include a consideration of available or credible disposal options and cost and safety issues as part of a process to identify the Best Environmental Practical Option (BEPO) for managing the sources. If disposal in a GDF is identified to be the BEPO, the Best Practical Means (BPM) for achieving the required performance of the packaged waste must then be identified.

**Figure 1 Properties of closed sources which may challenge waste package performance requirements**



The information in Figure 1 is presented as a series of statements relating to the source (or sources; as it is recognised that there may be more than one type of source in a waste stream, and that co-packaging may be the most practicable option). It identifies the information that will be required about sources to allow appropriate packaging plans to be developed. That is:

- the physical size of the closed capsule and the source material;
- the quantity and type of radioactivity present in sources;
- the physical form of the source material, i.e. whether it is gaseous, liquid or particulate; and
- the nature and quantity of neutron modifying or generating materials.

Additional data requirements may arise if it is found that specific measures are required to adequately mitigate the identified threats. For example, if there is sufficient particulate material present in a closed source to threaten requirements on immobilisation, then credit could be taken for the physical robustness of the source capsule; this will depend on a good knowledge of the properties of the source when manufactured, after storage, and its stability in the wastefrom environment. Information may be available from historical records.

This Section discusses the range of strategies that can be employed for the conditioning and packaging of closed sources; it is followed by Section 6 which provides a summary of the methods that have actually been used in the UK and internationally. It must be recognised that the strategies adopted overseas will not necessarily give rise to wastefrom and waste packages that are consistent with current UK requirements. However, none of the approaches described therein is expected to be fundamentally unacceptable, rather any approach adopted will need to be demonstrated and justified.

## **5.1 General approaches to waste packaging**

In the UK, ILW is typically packaged using one of three general approaches:

- Infilling of solid waste items within a waste container using an encapsulating grout;
- In-drum mixing of liquid, slurry or particulate wastes with a suitable inactive encapsulant within a waste container;
- Supercompaction of wastes within sacrificial drums or cans, followed by grout infilling within a waste container in which the supercompacted pucks of waste have been loaded. This is generally referred to as an 'annular grouted' wastefrom.

Of these three approaches, infilling would generally be considered the preferred approach for closed sources of the types physical sizes generally encountered in the UK. In-drum mixing would not be considered applicable to solid wastes such as closed sources, although it could be applied to liquid or particulate components of sources that have been isolated from the bulk source. Supercompaction is more usually used for 'soft' wastes and would not generally be applicable to sources with metal housings etc. However some features of an annular grouted wastefrom, such as the additional radiation shielding and/or physical protection provided by the grout annulus, may have relevance for sources with high surface dose rates of inventories of activity in particulate form.

## **5.2 Control of Inventory**

As discussed in Section 4 direct control of the radionuclide loading of waste packages containing closed sources will be required to allow the requirements of a number of the GWPS criteria (i.e. heat output, external dose rate etc) to be satisfied.

At its simplest, the total quantity of, say, activity in packaged sources could be limited to ensure compliance with defined limits; from a knowledge of the maximum activity associated with a given number or mass of sources, the radionuclide inventory per package could be bounded by limiting the waste loading to an acceptable number or mass of sources. Where there is a large variation in the activity associated with individual sources, and particularly where the waste is not to be co-packaged with other wastes, this may be unduly restrictive and excessively limit the resultant packing efficiency. For a less restrictive approach to be adopted, some characterisation of individual sources will be required. For waste streams containing a wide variety of sources, it will be beneficial to minimise the number of limits as far as is practicable. An example of a largely inventory-controlled waste packaging process that has been endorsed by way of the LoC process is provided in Section 6.

It is clear that the segregation of different sources as they arise affords significant benefits when packaging is undertaken. It is therefore recommended that new arisings of sources are segregated according to type and activity level as far as is practicable. This may be seen as representing BPM although, if such an approach were to result in an increased number of waste packages for a particular wastestream, such wider issues would need to be considered.

Limits may be defined to take account of GWPS requirements in terms of:

- total activity;
- total heat output, including the effect on wastefrom evolution;
- waste package external dose rate;
- waste package performance under impact and/or fire accident conditions (e.g. number of A<sub>2</sub> multiples; quantity of mobile and/or volatile radionuclides);
- quantity of radioactive gas released, or;
- criticality safety.

For some radionuclides, it may be feasible to claim the benefit of decay storage to allow the activity level to fall to levels that would not be expected to compromise the performance of the wastefrom and waste package. Decay storage will only be appropriate for those sources containing radionuclides that have sufficiently short half-lives (i.e. up to ~10 years). This option may also be precluded if the timescales for achieving packaging are too short to allow sufficient decay. It should be remembered that radioactive decay will take place between the time of packaging, and the time of waste package transport to a disposal facility, a time that is expected to extend to many decades for most packaged waste. Therefore, although a waste package may exceed certain limits at the time of packaging, it may be compliant by the time of transport. For example, a waste package containing sufficient Co-60 (half-life 5.3 years) to exceed the requirements for heat output and/or dose rate when packaged will have a considerably lower inventory after an extended period of interim storage (only ~0.1% of the original activity will remain after 50 years). If such arguments are used in support of packaging proposals, the following must be taken into account:

- the effect of the inventory throughout interim storage on wastefrom and waste package evolution (see Section 4.1.4), and;
- current uncertainty regarding the date at which a disposal facility for ILW may become available, and hence the earliest date of transport.

It is possible that some individual sources have a sufficiently large radionuclide inventory that they will exceed waste package activity limits even when packaged alone. In such

cases, it may be necessary to size-reduce the items so that the pieces produced can be packaged. For closed sources, this will result in a loss of any containment provided by the capsule and will expose the source material itself. In this event, attention will need to be given to the impact of the loss of containment, and to whether any additional measures are required to ensure compliance.

When defining limits on sources, it will be necessary to take into account the inventory of any co-packaged wastes, i.e. any limits on sources should be clearly linked to limits on the waste package as a whole and the radionuclide inventory of the other wastes.

As well as control of radionuclides, it may be necessary to control the inventory of hazardous materials and/or neutron modifying/generating materials. The same approaches would be employed if this were the case.

### **5.3 Immobilisation**

#### **5.3.1 Particulates, free liquids and hazardous materials**

For waste packages that contain, or may contain, the potentially significant quantities of mobile activity, as defined in Section 4.1.1, justification of adequate immobilisation by the waste container and wasteform should be provided as part of waste packaging proposals. Achievement of demonstrably acceptable immobilisation may rely on the properties of the sources themselves, the wasteform and waste container, the integrity of specifically designed engineered barriers within the wasteform, or a combination of two or more of these.

Free liquids should be excluded from waste packages whenever practicable. Accordingly, it is considered that any closed source incorporating free liquids above the threshold activity levels identified above should be opened to allow that liquid to be immobilised, for example by mixing with an encapsulant. Where liquid-bearing sources form only a small part of a larger waste stream, it may be most practicable to undertake mixing on a small scale, then to package the resultant solid wastes as for other ILW solids (e.g. by grout-infilling or supercompaction followed by encapsulation of the pucks).

It could be argued that the best immobilisation could be achieved if any hazardous materials, particulates, or materials that could degrade to form these, were removed from sources to allow intimate conditioning by mixing with an appropriate encapsulant. This may not be practicable, and is likely to be undesirable. As an alternative, it may well be possible to make a sound case for packaging intact sources.

Whenever possible, sources are manufactured using radioactive materials with low dispersibility, precisely to minimise the potential for the spread of contamination. For example, the source material may be present as an alloyed metal, or as a fused pellet. The majority of source radionuclides are expected to be in a robust form themselves; mostly as metals, ceramics or salts pressed into pellets. However, evidence suggests that ceramic materials used in closed sources tend to degrade over their 'working life', which may be only of the order of 10-15 years and this may result in the generation of potentially mobile particulate material. Similarly, corrosion of metal or alloy source matrices may lead to the generation of particulate material, and the radiolytic degradation of polymers, e.g. epoxy resins in homogeneous sources, could generate a mobile source term. The evolution of the source material should be taken into account when developing arguments that rely on the long-term retention of radionuclides by the source.

If a waste packaging proposal takes credit for the integrity of the source material itself, then the following should be included in support of that proposal:

- details of the nature and properties of the source material should be reported, including activity, composition, methods of manufacture;
- a consideration of the potential for degradation of the source over the relevant waste package integrity timescale (defined by the GWPS as 500 years) and under an appropriate range of environmental conditions. The following should be taken into account:
  - for metals, the effects of corrosion;
  - for other materials, chemical effects (such as alkaline hydrolysis), radiolysis and microbial degradation.
- The conditions to which the source material will be exposed. For example, is there expected to be interaction with the encapsulating material, or will the source containment prevent it?;
- The effects of waste handling, treatment, packaging and transport; these may be sufficient to physically degrade the source material so that immobilisation is no longer provided. A potentially notable example is supercompaction.

For closed sources with a high degree of integrity provided by, for example, stainless steel capsules around the active source material, it may be possible to take credit for this primary containment barrier. For proposals that take credit for immobilisation provided by the source containment, details of the source containment's composition and methods of manufacturing should be supplied, and consideration should be given to the expected lifetime of that source containment. Corrosion is expected to be relevant, as is the potential for the source to be ruptured as a result of gas pressurisation (principally arising from alpha decay and subsequent helium generation) as this would threaten the integrity of the source enclosure (see Section 4.1.2).

Corrosion of steels is expected to proceed at a slow rate, so that those closed sources comprising a continuous steel capsule may well remain intact over the relevant timescales. If such sources are to be co-packaged with other wastes, then consideration should be given to whether their presence will cause accelerated or localised corrosion to such an extent that the steel capsule is breached, and waste package performance is undermined. Examples of such materials include chlorides and electro-chemically dissimilar materials such as graphite. It is also conceivable that deleterious interactions between the source containment and the source material itself could promote degradation of the containment. For examples, old sources could contain radionuclides as chloride salts.

Many closed sources have engineered 'windows' to allow transmission of x-rays and other radiations that may render them susceptible to corrosion and/or leakage [12]. For example, Am-241, Cd-109, Cm-244, Fe-55 and Pu-238 sources typically have beryllium 'windows' which are likely to be susceptible to corrosion in a high pH environment typically found in inorganic cement immobilising grouts. Other closed sources may be hermetically closed, all-steel capsules but with thin machined windows of the order of only tens of microns thick to allow transmission of alpha or low-energy beta emissions. Further, the windows may be brazed in place, presenting a potential focus for corrosion. However, such loss of source integrity may not be significant to the overall performance of a properly designed and manufactured waste package in which the barrier originally provided by the source housing was in addition to those provided by the wasteform and waste container.

Although some sources may be regarded as *special form radioactive material*<sup>9</sup> under the IAEA Transport Regulations [10] when manufactured, this status will need to be justified and may be subject to satisfactory periodic inspection and manufacturing records; beyond the recommended working life of the source, examination of the source and assessment of the design characteristics would be required. It is considered impractical to expect sources designated as special form radioactive material to continue to meet the definition indefinitely. Indeed, demonstration of compliance with the requirements for such materials is likely to be rendered very difficult by packaging; accordingly radionuclides should not necessarily be considered as being such for the purposes of transport or any other phase in their management.

It may be possible to demonstrate that the response of the waste package to impact accident is such that the waste will not be exposed under the most challenging conditions, thereby preventing release of any particulates or hazardous materials present. Impact accident performance is a complex function of the properties and characteristics of the waste, wasteform and container. However, it may be possible to improve impact performance to the required extent by, for example, using a high-integrity container, by providing a waste-free annulus around the waste or by simply placing the source(s) towards the centre of the wasteform and thereby providing greater protection in an impact accident. Proposals that take credit for impact performance to justify the achievement of adequate immobilisation may need to be supported by experimental evidence; it may be possible to use the results from tests undertaken and reported in support of analogous waste packaging proposals, although the use of any such analogue would need to be carefully justified and supported.

For sources requiring a high degree of containment, or with a low inherent integrity, it may be appropriate to provide an additional physical barrier, such as a can, to over-pack the source or sources. This approach has been widely adopted overseas, particularly for sources containing high levels of activity, and especially where the isotopes present are long-lived (see Section 6). In practice, this is unlikely to be an attractive option for widespread application because of the cost and dose uptake associated with over-packing. As with other containment barriers, the potential for degradation of the additional capsule or can should be addressed as part of the packaging proposal.

### **5.3.2 Radionuclides present as gases**

Although there will be some diffusion of gases from the source through its casing, the rate will be slow, so that if it can be demonstrated that sources will effectively retain their gaseous contents during the 28 days assumed as the maximum period of transport. Accordingly, the release of gaseous radionuclides from intact sources are of little consequence to this aspect of transport safety.

However, if the integrity of the sources is lost before or during the period of transport these gaseous radionuclides may leak into the transport container cavity and so escape from it into the environment. In practice, it may be difficult to demonstrate conclusively that such sources will not fail during transport and such sources would need to be considered in the same way as other ILW containing, and capable of releasing, radioactive gases.

The waste, wasteform and waste package features for which credit might be taken are similar to those identified in Section 5.3.1, and can be summarised as:

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<sup>9</sup> Defined as 'either an *indispersible solid radioactive material* or a *sealed capsule containing radioactive material*' ([10] Para 239)



- The continuing integrity of the source containment. This may be difficult to demonstrate for Kr-85 and H-3 sources as-manufactured, since they incorporate thin windows to allow transmission of the relatively low-energy emissions.
- Additional containment provided by an additional welded container around the source. The long-term integrity of such a container, and its existence as a precluded 'hazardous' item (i.e. a sealed container) would need to be considered.
- Hold-up of the gases by an encapsulant. Cementitious encapsulants may not afford particularly good retention of such mobile species as isotopes of hydrogen, krypton and radon, and there may be significant benefit in the development and use of polymers. *Guidance Note on the Use of Organic Polymers for the Encapsulation of Intermediate Level Waste: Review of Candidate Materials, WPS/901*, provides information regarding a number of polymer encapsulants that may be considered in this context.
- Hold-up of the gases by the container. The escape of gases via any filtered vent will need to be taken into account. There is scope for the use of non-vented containers, but this will only be appropriate for waste packages in which the rate of gas generation is so low that pressurisation of the matrix and container will not result over a long period. In practice, gas generation mechanisms such as the radiolysis of any encapsulant are likely to render this approach impractical.

Existing guidance (i.e. *WPS/902*) provides detailed information on the waste package features that can be adopted to reduce radon emanation to an acceptable level, and on the arguments that can be used to support packaging proposals involving radon-generating wastes. Similar approaches and arguments may be applicable to packaging radioactive gas-bearing closed sources.

No specific guidance is available for radioactive gas generation during repository operation or subsequent to repository closure. It is possible that no such limits will be specified that will be applicable to individual waste packages. Accordingly, this will be assessed on a case-by-case basis by way of the LoC process.

#### **5.4 Removal of Hazard**

Section 4.1.2 considered how closed sources may constitute 'hazardous materials', as defined by the GWPS. Some sources, by virtue of their size and inventory, which could result in high internal pressures, may be considered as pressurised containers and, therefore may be excluded unless depressurised or vented. This would almost certainly have implications for source integrity that will need to be considered in terms of waste package properties and performance; the deliberate venting of closed sources that might otherwise become pressurised will incur some loss of containment that would otherwise be provided by the capsule. However, such loss will be predictable, and the other components of the wasteform and waste package would be designed to ensure adequate containment overall. If failure were to occur as a function of pressurisation, then the outcome and timing of that failure would be much more difficult to predict, and this may represent a significant uncertainty. Where there is the potential for source failure as a result of pressurisation, it is therefore recommended that such sources be vented, and other features of the wasteform used to ensure that adequate immobilisation is achieved. In this way, the potential hazard from pressurisation will be removed. Alternatively it may be that the consequences of source failed due to over-pressurisation are such that the overall performance of the waste package is not affected to a significant degree. It may be possible that reasoned argument can be used to show that the consequences of the eventual failure of a source in the future are less important than those associated with forced venting during packaging.

Source materials that pose a potential hazard because of their reactivity or toxicity could be rendered non-hazardous by removing them from any source containment, and converting them to a less hazardous form, e.g. through reaction to form an inert compound. This option is likely to be unattractive, and should only be pursued if the hazard posed is assessed as being potentially significant and the required degree of isolation cannot be provided. Early dialogue to determine the potential significance of any such hazardous materials is recommended. Details of the nature and quantity of hazardous source materials will need to be provided as an input to assessment.

## **5.5 Control of Distribution**

As discussed in Section 4.1.4 the issue of the inhomogeneity of activity distribution that will inevitably result from the presence of closed sources in a waste package is one which may need management. The distribution of sources within the wasteform may need to be controlled to improve uniformity in wasteform heating and self irradiation of the wasteform. Failure to do so could result in wasteform damage by excessive temperature gradients or irradiation. Additionally, external dose from the waste package can be reduced by placement of sources towards the centre of the wasteform.

Clearly, wastes near the centre of the wasteform will be shielded more than those adjacent to the drum wall. Accordingly, high activity gamma- and/or neutron-emitting wastes could be loaded at or near the centre of the wasteform. If credit is taken for shielding provided by the wasteform, then it should be ensured that the distribution of the waste, and any other relevant features such as co-packaged wastes (where credit is taken for shielding by them) is not materially changed during other stages of the waste packaging process, e.g. grout infilling. Perhaps the simplest method of increasing control of waste distribution is the provision of a waste-free annulus at the container wall. This could be achieved by one of two methods:

- the use of a waste container that incorporates a pre-cast annulus. This has the advantage of a high degree of process control, and a greater confidence in the properties of the annulus as a result, or;
- the use of a basket or other container furniture to hold the waste away from the container walls during loading, followed by infilling of the waste, basket and annular gap with an appropriate encapsulant.

A higher degree of control could be achieved using more complex arrangements of container furniture. Ultimately, furniture could be designed so that the exact positioning of a source within the wasteform is known, and this would allow for the maximum amount of credit to be taken for wasteform self-shielding. However, such an approach may well carry penalties in terms of waste loading, process complexity, operator dose uptake and waste package production cost, and alternative measures may be more appropriate.

The design of any furniture should take into account the effect of grout infilling; low-density (i.e. less dense than the grout) wastes or over-packs could be displaced by the grout, and rise to the top of the wasteform.

Where the distribution of sources within a waste package is an important factor determining waste package performance, this should be reported in the LoC submission, along with the methods to be used to ensure adequate control, and reflected in the Waste Product Specification for the proposed waste packages<sup>10</sup>.

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<sup>10</sup> See *Waste Product Specification. Guide to Structure and Format, WPS/620*.

## 5.6 Provision of Additional Shielding

Even if care is taken in loading a package, it may not be possible to package some sources and meet the dose rate limit without increasing the amount of shielding present or physically reducing the size of the source (see Section 5.2).

Gamma dose rates will be reduced most effectively by materials with high density. These could be present as co-packaged wastes, void fillers, encapsulants, inner containment vessels or waste container features, surrounding a source or sources.

If shielding provided by co-packaged wastes is to be taken into account, then it will need to be demonstrated that the configuration for which credit is taken is reproducible; the required degree of control on waste loading may be excessively onerous.

Small containment vessels (i.e. smaller than the outer waste container) could provide shielding themselves (for example, thick-walled steel or lead cans), be infilled with a high-density encapsulant such as a metal or iron-shot concrete, or void-filled with a high-density material such as iron shot or lead pellets. The use of lead cans, encapsulants and pellets has been adopted overseas, as described in Section 6.

Shielding could be provided by the use of a waste container that provides a greater degree of shielding than the standard containers. Thick-walled containers made from ductile cast iron could be considered, although it must be recognised that these drums typically have mass in excess of the waste package mass limits defined in the GWPS, so that early discussion with RWMD is strongly recommended if such an approach is considered. Containers that incorporate a waste-free annulus would also provide additional shielding, particularly if the annulus is made using a high-density material such as iron-shot concrete. Approaches to the fabrication of a waste-free annulus have been discussed in Section 5.5.

Attenuation of neutrons from neutron sources is a complex process. Shielding is usually comprised of predominantly light elements, the most common being hydrogenated materials such as concretes and plastics; for example, polythene. The use of polymers for neutron attenuation has been endorsed for some wastes (see Section 6). As with the high-density materials discussed for general radiation shielding above, low-density materials affording neutron attenuation could be present as:

- small containers surrounding the source or sources;
- encapsulants; for polymeric materials, it would be desirable to minimise the quantity used by in-can grouting the neutron sources, rather than polymer encapsulating the entire wasteform. The use of a lead-based alloy containing cadmium as an encapsulant is described in Section 6;
- void fillers; the use of borosilicate glass powder for neutron attenuation is described in Section 6, or;
- as part of the container; a polymer-filled annulus could be used, noting previous comments regarding quantities of organic materials. It might be feasible to introduce neutron-attenuating materials to a cementitious grout, although their effect on cement hydration (e.g. boron), toxicity (e.g. cadmium) and other package features would need to be addressed.

In all of the above cases, demonstration of the continued effectiveness of any measures taken to provide additional shielding would be necessary. Such demonstration would be particularly important if the measures were also to be relied upon for ensuring the criticality safety of waste packages. The timescale for such a demonstration would need

to extend to at least that anticipated for interim surface storage, transport and the operational period in a GDF; the GWPS suggests that a period of ~200 years would conservatively encompass these phases of the management of the waste packages.

## **6 EXAMPLES OF TECHNIQUES USED FOR THE CONDITIONING OF CLOSED SOURCES**

This Section provides a summary of approaches that have been adopted, internationally and in the UK, to condition closed sources so that they are consistent with requirements for transport, storage and/or disposal. Some of the techniques used may be applicable to the range of closed sources, and the packaging requirements, applicable to the UK. This review has drawn on documents identified using the International Nuclear Information System (INIS) database, and advice issued to waste packagers following the LoC assessment of relevant packaging proposals.

### **6.1 International Experience**

The literature reviewed cites a range of techniques that have been used internationally for the conditioning and packaging of closed sources. The detailed reasons for the selection of particular conditioning methods are rarely reported in the literature, but this can be inferred. There are a number of approaches that can be identified, and these can be summarised as the use of:

- volume-reduction;
- small, welded containers;
- high-density, low-melting-point metal encapsulants and lead shielding;
- void fillers (i.e. loose powders or pellets that do not form a coherent monolithic solid);
- low-density materials and encapsulants that increase neutron shielding;
- cementitious encapsulants, and/or;
- 'enhanced' containers.

Essentially, each of the approaches shown above, with the exception of volume-reduction, acts to provide a number of barriers to the release of radioactivity and/or radiation from the sources. In many cases, several of these techniques are reported to have been used in concert to provide the required degree of isolation and shielding.

The use of compaction to achieve volume-reduction has been reported in one reference [14], but this approach is limited to sources having a low activity (threshold activity for compatibility with compaction is not stated). Compacted wastes are over-packed.

The use of welded capsules to over-pack sources has been widely reported [14, 15]. The capsules are typically fabricated from stainless steel, although alternatives are cited; reference [15] reports that, in Latvia, radium-bearing sources are conditioned using a welded copper capsule, over-packed with a welded stainless steel capsule. Reference [16] cites the use of a borosilicate glass powder to void-fill the capsule surrounding a neutron-emitting (americium/beryllium) source, thereby increasing neutron attenuation. Once welded shut, the capsules containing the sources may be further over-packed using a range of measures to produce a transport or disposal package.

The use of lead and lead-based alloys has been reported in a number of documents. Specific uses that have been cited are:

- lead containers to provide additional shielding for sources that have been packed into welded stainless steel or other capsules [14, 15, 17];
- lead-based, low melting-point alloys (e.g. 50:20:20:10 bismuth/lead/tin/cadmium) used to encapsulate sources that have been loaded to stainless steel cans [16, 18]. Any cadmium in the alloy provides neutron attenuation [16];
- lead pellets used to provide a void-filler for sources loaded into stainless steel containers [15]. The intention is assumed to be the provision of additional shielding.

In almost all of the cases identified, lead is used at relatively small scale, and the lead-contained or –conditioned source is further over-packed for onward waste management. In only one case has the use of a low-melting point metal to ‘complete’ the wasteform been reported; some gamma-emitting sources are metal-encapsulated within 200 litre drums in Latvia [15].

The use of void fillers to fulfil a range of purposes has been reported. The use of borosilicate glass powder for neutron attenuation and lead pellets to provide shielding has already been described above. Sand has been used in Belgium as a simple void filler that allows for retrieval of sources for onward waste management [16]. Reference [15] reports the use of ‘heated quartz’ for surrounding alpha-emitting sources loaded to stainless steel containers. Although it is not clear whether the heating applied is sufficient to cause fusion of the quartz to form a solid monolithic encapsulant, the high melting point of quartz (1610°C) suggests that the quartz is more likely to be present as a sand-like material as in the previous example. Activated carbon has been used as a void-filler for closed sources within stainless steel cans in Portugal [14].

High-density polyethylene (HDPE) and wax have been used to provide neutron attenuation [14].

Cement and concrete have been widely adopted as components of waste packages containing closed sources. Both as-manufactured and over-packed sources (e.g. sources within welded capsules and/or lead shielding) have been encapsulated using cementitious infilling grouts [14, 15, 16, 17]. The reasons for using such encapsulants has not been described in the documents consulted, but they are expected to play several roles, including:

- shielding;
- minimisation of voidage;
- prevention of retrieval, i.e. increased security during prolonged storage;
- chemical conditioning of steel and other waste package components.

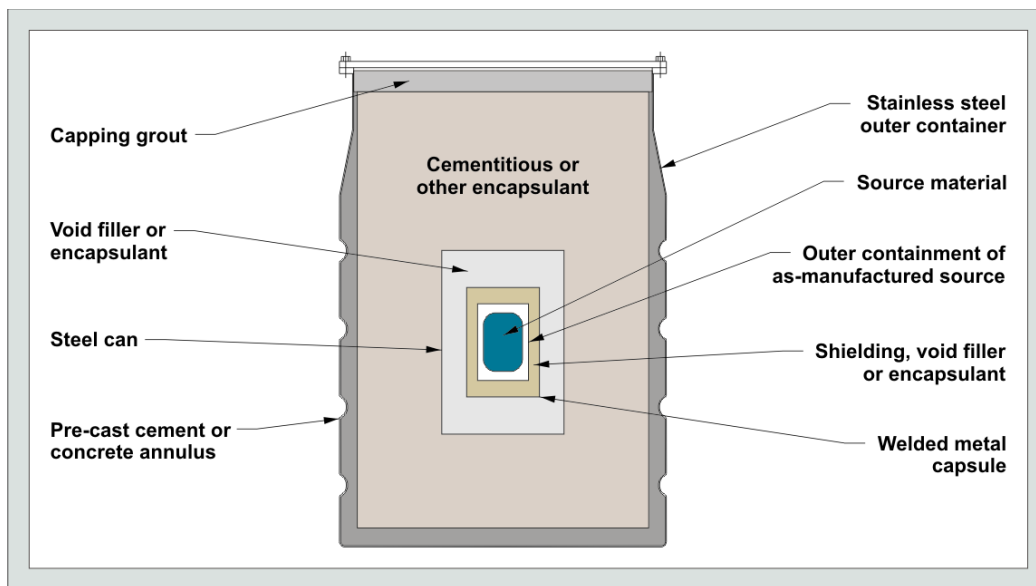
Concrete boxes have also been used as the outer waste container [15].

There are several examples of the use of steel containers that incorporate a pre-cast cement or concrete annulus [14, 16, 17, 18]. Sources within the containers can be in their as-manufactured form without additional packaging, in which case container furniture may be used to make retrieval of the sources more difficult (i.e. to increase security). In other cases, the sources may have been over-packed one or more times, e.g. by loading into welded capsules, and are also encapsulated within the outer waste container.

Figure 2 summarises the approaches that have been reported. Clearly, the number and type of barriers that may be required in order for a waste package containing closed sources to comply with the relevant regulations will depend on a potentially broad range of factors, including:

- the type, radionuclide inventory, construction, age and condition of the sources;
- the nature and duration of future stages of waste management;
- the WPS or, in the case of an operational facility, the Waste Acceptance Criteria (WAC) that the package must meet.

**Figure 2 Summary of approaches used to condition and package closed sources**



## 6.2 UK Experience

Packaging proposals for closed sources with levels or types of activity that are incompatible with processes generally used for more typical ILW have been submitted by UKAEA for LoC assessment as part of the strategy for packaging Remote-Handled ILW (RHILW) at Harwell.

Proposals by UKAEA to package RHILW, including a number of different types of closed source, within 'enhanced' 500 litre Drums that comprise an outer stainless steel drum, a cementitious annulus and an inner stainless steel liner, have been endorsed by way of the LoC process. The wastes are loaded to the waste containers for interim storage prior to the addition of a fluid cementitious encapsulant at a future date. Various measures are in place to give confidence that the closed sources loaded to the containers will be compatible with GWPS requirements once grouting has been undertaken; the remainder of this section identifies those measures.

An upper limit on the radionuclide inventory of americium/beryllium (Am/Be) neutron-sources loaded loose to each waste container has been defined on the basis of the maximum inventory that can be packaged in a single drum without the need for additional neutron attenuation. The limit has been defined using dose rate modelling and by assuming that the sources could be located adjacent to the drum wall. Larger Am/Be sources can be accommodated if they are over-packed using a polythene liner or pot, which attenuates dose. Advice arising from the LoC assessment of this proposal has

recommended that the pots be the minimum thickness required to sufficiently attenuate the neutron dose associated with Am/Be sources within specific activity categories; in this way, the quantity of organic material introduced to a GDF will be minimised. From the agreed limits on Am/Be sources, UKAEA developed limits for other neutron-generating sources, taking into account the relative neutron activities and half-lives of other radionuclides.

Since the loading of loose Am/Be sources limited by neutron dose rate had been endorsed by way of the LoC process, UKAEA defined a limit for the activity of individual loose-loaded sources of other types based on the number of  $A_2$  multiples present in an Am/Be source with the same activity; this approach was also endorsed. A limit on the total activity of all sources loaded into a single drum was defined to ensure that the heat output from a worst-case combination of sources adhering to all other limits would not exceed an agreed limit.

Although no limits were placed on the mixtures of sources that could be co-packaged, it was agreed that the combined neutron and gamma dose rate at 1m from a bare drum (rather than four 500 litre Drums in a shielded waste transport container) would be limited to  $0.1\text{mSvhr}^{-1}$ . In this way, it is intended that any heterogeneity in dose rate could be accommodated during future stages of waste management.

Early advice noted that gaseous sources were outside of the scope of the assessment and should, therefore, be excluded from the wastes packed with RHILW. It was recognised that, for historical wastes, complete exclusion might not be practicable. It was recommended that, for the purposes of developing proposals for packing gaseous sources that could not practicably be excluded, it should be assumed that the entire contents of gaseous sources could potentially be released to the cavity of the transport container, and that this pessimistic but bounding assumption could be used to develop a limit for gaseous sources.

Proposals have been made for the packaging of radon-generating Ra-226 sources present in RHILW and, although these have not been endorsed at the time of writing, the following advice has been given, which has general relevance to the to the packaging of radium sources, and other wastes that have the potential to release radioactive gases:

- the use of a 'decay tube' is likely to be beneficial in reducing the release of radon gas by ensuring that it decays to a solid isotope before release;
- the use of an infilling material to surround radium-sources within steel cans is likely to be beneficial, since it reduces the reliance on continued integrity of the cans themselves. It is noted that cementitious matrices are unlikely to afford the required degree of hold-up, but that polymer matrices can be shown to be acceptable;
- cementitious matrices surrounding in-can encapsulated radium-sources may afford little radon-retention, partly because the distribution of the encapsulated items within the drum may reduce the thickness of grout through which the radon may have to travel;
- the potential for pressurisation of welded cans by helium (from alpha-decay) and radon, and the potential for gas generation through degradation of co-packaged wastes, are potential issues that need to be assessed on a case-by-case basis.

It is clear that a sound knowledge of the radionuclide inventory, physical form of radionuclides and the physical robustness of the sources is of fundamental importance in developing and justifying appropriate packaging proposals.

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The methods that have been endorsed, or at least assessed as beneficial, to allow packaging of closed sources within Harwell RHILW can be summarised as:

- inventory control - exclusions and limits to be met have been developed, and relate to dose rate, heat output and activity (i.e.  $A_2$  multiples);
- use of polyethene pots to increase the attenuation of neutrons when applicable;
- use of polymer encapsulants within cans to increase hold-up of radon from radium sources;
- use of decay tubes to afford hold-up of radon, and;
- use of an enhanced container.



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**APPENDIX A TYPICAL CLOSED SOURCES AND THEIR APPLICATIONS**

Radio-nuclide	Application	Typical Inventory when Manufactured	Maximum Inventory after 30 years
Am-241	Gamma back-scatter thickness gauging	37MBq-3.7GBq	3.5GBq
	Gamma transmission thickness gauging	370MBq-37GBq	35GBq
	X-ray Fluorescence Analysis	111MBq and 370MBq	353MBq
	Level Gauging	3.7GBq	3.5GBq
	Smoke Detection	Currently 40kBq Historically up to 4MBq	3.8MBq
	Lightning Preventors	Up to 9 x 15.9MBq foils per preventor	136MBq
Am-241	Neutron Moisture Gauging	1.11GBq-9.25GBq	8.8GBq
Ba-133	Various, e.g. Gamma Standards	37-370MBq	50MBq
Cd-109	X-ray Fluorescence Analysis	37-740MBq Typically ~100MBq	55 Bq
Cf-252	Neutron Moisture Gauging	0.2MBq-4GBq	1.52MBq
Cm-244	X-ray Fluorescence Analysis	440MBq-44GBq Typically 1.1GBq and 3.7GBq	14GBq
Co-57	X-ray Fluorescence Analysis (also 'flood' sources for medical calibration, $\gamma$ )	Up to 370MBq	Nil
Co-60	Gamma transmission thickness gauging	37MBq-3.7GBq	70MBq
	Level Gauging	Up to 185GBq	3.59GBq
	Sterilisation Plants	4PBq-200PBq	4PBq
	Industrial Radiography	Up to 45TBq	872GBq
	External Beam Therapy	Up to 410TBq	8TBq
Cs-137	Gamma back-scatter thickness gauging	Up to 1.85GBq	930MBq
	Gamma transmission thickness gauging	370MBq-37GBq	18.6GBq
	Level Gauging	Up to 370GBq	186GBq
	Medical Brachytherapy	Up to 74GBq	37GBq

<b>Radio-nuclide</b>	<b>Application</b>	<b>Typical Inventory when Manufactured</b>	<b>Maximum Inventory after 30 years</b>
Fe-55	Electron Capture Detection	185MBq	80kBq
Gd-153	Bone Densitometry and Real Time Radiography	37GBq	Nil
H-3	Electron Capture Detection	37-185GBq	34GBq
	Gaseous Tritium Lighting Devices	37GBq-1TBq	184GBq
Ir-192	Medical Brachytherapy	Up to 370GBq	Nil
	Industrial Radiography	Up to 11TBq	Nil
Kr-85	Beta back-scatter thickness gauging	37-185MBq	27MBq
Ni-63	Electron Capture Detection	370MBq	300MBq
	X-ray Fluorescence Analysis	3.7MBq-1.85GBq Typically 740MBq)	1.5GBq
Pm-147	Beta back-scatter thickness gauging	37-185MBq	67kBq
Po-210	Static eliminators	Up to 7.4GBq	Nil
Pu-238	XRF Analysis (historical)	1.11GBq-3.7GBq	2.9GBq
	Medical (pacemaker)	200GBq	200GBq
Ra-226	Medical Brachytherapy	4MBq – 4GBq	4GBq
	Lightning Preventors	Up to 9 x 2.96MBq foils per preventor (~25MBq/item)	25MBq
	Smoke Detectors	30kBq	30kBq
Ru-106	Beta back-scatter thickness gauging	37-185MBq	< 1 Bq
Se-75	Industrial Radiography	1.11TBq	Nil
Sr-90	Beta back-scatter thickness gauging	37-185MBq	90MBq
Tl-204	Beta back-scatter thickness gauging	37-185MBq	750kBq
Depleted uranium	Integral shielding for industrial radiography and external beam therapy equipment.	Up to 500 kg per unit (10GBq)	10GBq
Yb-169	Industrial radiography	370GBq	Nil

**APPENDIX B THERMAL EFFECTS OF A CLOSED SOURCE**

Determination of the thermal effects of a large Cs-137 source in a 500 litre Drum Waste Package

Assumptions:

- Source containing 80TBq Cs-137 Radiogenic heat output,  $Q = 10W$
- Cylindrical capsule, 65mm high, 36mm diameter
- Source placed at centre of waste package
- Waste Package: 500 litre Drum, 1200mm high, 800mm diameter
- Cement based wasteform, thermal conductivity,  $k = 0.7WK^{-1}m^{-1}$
- Heat from sources passes through a series of cylindrical shells of radius  $r$ , thickness  $\delta r$ , and height/diameter ratio of 1.8

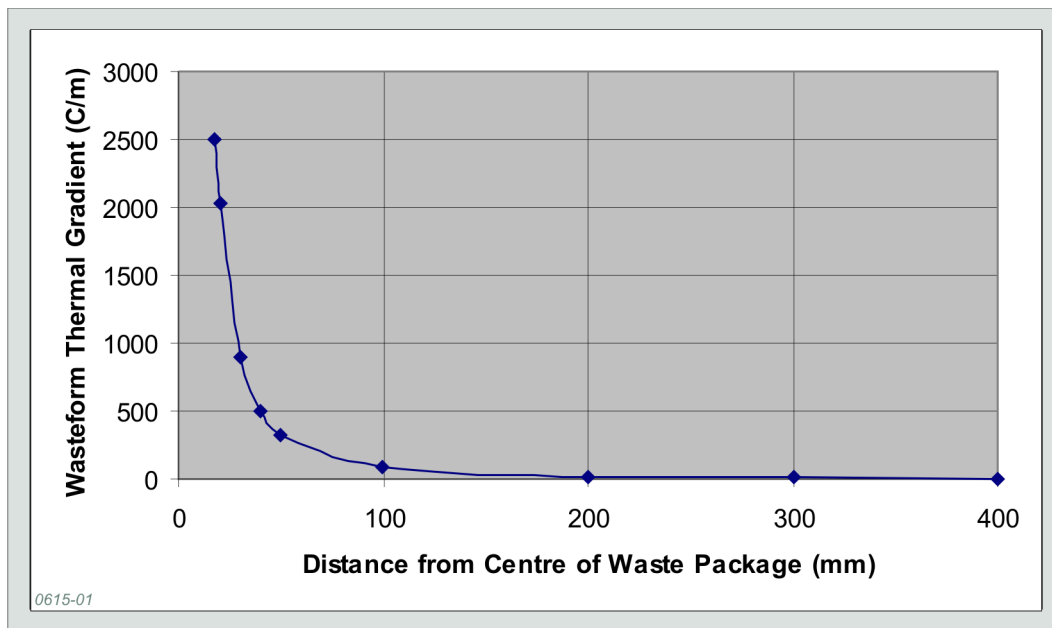
$$\text{Total external surface area of cylindrical shell, } A = 2\pi r^2 + 2\pi r \times 1.8r = 5.6\pi r^2$$

$$\text{Heat flow through shell, } Q = kA\delta T/\delta r$$

$$\text{Thermal Gradient} = \delta T/\delta r = Q/kA = 10/(0.7 \times 5.6\pi r^2) = 0.81/r^2$$

Figure B.1 illustrates that the thermal gradient is very high (i.e.  $>1000^\circ C m^{-1}$ ) in the immediate vicinity of the heat source but falls by an order of magnitude  $\sim 100mm$  from the surface of the source

**Figure B.1 Thermal gradient in the vicinity of a closed source**



Integrating the expression for thermal gradient, and assuming a waste package surface temperature of  $50^\circ C$ , results in an expression for wasteform temperature:

$$T = 48.0 + Q/5.6\pi kr = 48.0 + 0.81/r$$

Figure B.2 illustrates this expression and shows that, at the surface of the source, temperatures approaching  $100^\circ C$  are possible although this would fall below  $80^\circ C$  at 25mm from the source.

Figure B.2 Temperature in the vicinity of a closed source

