Radioactive Waste Management

WPSGD no. WPS/929/02

Geological Disposal:

Thematic Guidance on the Management of Larger PCM Waste Items

September 2017

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Bibliography

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WASTE PACKAGE SPECIFICATION AND GUIDANCE DOCUMENTATION

GUIDANCE ON THE PACKAGING OF LARGER PCM WASTE ITEMS

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

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

This document provides guidance on the packaging of larger plutonium contaminated material (PCM) waste items[1]. Larger PCM items are defined as items where inclusion within existing PCM waste treatment processes is not considered practicable and the items are either:

- too large to be placed within existing RWM approved containers that are then placed in a Type B package without additional size reduction;
- will challenge existing disposal requirements unless further size reduction or conditioning is undertaken (e.g. voidage minimisation); or
- do not meet the criteria for Low Specific Activity (LSA)[2] or Surface Contaminated Object (SCO)[3] and so are not suitable for packaging within Type IP-2 packages such as 2 metre, 4 metre and 6 cubic metre concrete boxes (definitions from the RWM Glossary [1]).

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

WPSGD DOCUMENT NUMBER WPS/929 - VERSION HISTORY		
VERSION	**DATE**	**COMMENTS**
V1	March 2017	New document issued to waste packagers for use.
V2	September 2017	Minor changes to address further stakeholder comments.

[1] 'PCM' is the term used throughout the guidance, but that could be taken to encompass other wastes with similar characteristics (relatively high fissile content, low dose rates/contact handleable, uranium and/or transuranic content)

[2] Low Specific Activity (LSA) is a material classification defined by the IAEA Transport Regulations as ‘*Radioactive material which by its nature has a limited specific activity (i.e. activity per unit mass of material), or radioactive material for which limits of estimated average specific activity apply*.’

[3] A Surface Contaminated Object is a solid object which is not itself radioactive but which has radioactive material distributed on its surfaces.

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Abbreviations and acronyms used in this document

ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
AWE	Atomic Weapons Establishment
BAT	Best Available Technique
CHILW	Contact Handleable Intermediate Level Waste
DSRL	Dounreay Site Restoration Ltd
DSSC	Disposal System Safety Case
EPR10	Environmental Permitting (England and Wales) Regulations 2010
gCSA	Generic Criticality Safety Assessment
GDF	Geological Disposal Facility
GSL	General Screening Level
GWB	Gemini Waste Box
HAW	Higher Activity Waste
HSE	Health and Safety Executive
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
ITEAP	Integrated Test, Evaluation and Acceptance Plan
LHGW	Low Heat Generating Waste
LLW	Low Level Waste
LLWR	Low Level Waste Repository
LoC	Letter of Compliance
LSA	Low Specific Activity
LWC	Large Waste Container
LWTC	Large Waste Transport Container
NDA	Nuclear Decommissioning Authority
ONR	Office for Nuclear Regulation
PCM	Plutonium Contaminated Material
REPs	Radioactive Substances Regulation Environmental Principles
ROCK	Retention Of Critical Knowledge

RWM	Radioactive Waste Management Ltd
RWMC	Radioactive Waste Management Case
SAPs	Safety Assessment Principles
SCO	Surface Contaminated Object
SEPA	Scottish Environmental Protection Agency
SFAIRP	So Far As Is Reasonably Practicable
SL	Sellafield Ltd
SLC	Site Licence Company
TSM	Total System Model
U-ILW	Unshielded Intermediate Level Waste
WAC	Waste Acceptance Criteria
WIPP	Waste Isolation Pilot Plant
WPS	Waste Package Specification
WPSGD	Waste Package Specification and Guidance Documentation
WTC	Waste Treatment Complex

1. Introduction

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

The packaging specifications form a hierarchy which comprises three levels:

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

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

The WPSGD includes a range of WPS for different waste package types together with explanatory material and guidance that users will find helpful when it comes to application of the WPS to practical packaging projects. For further information on the extent and the role of the WPSGD, reference should be made to the *Introduction to the RWM Waste Package Specification and Guidance Documentation* [3].

The requirements for waste packages containing intermediate level waste (ILW), and wastes with similar radiological properties, are defined by the *Generic specification for waste packages containing low heat generating waste (LHGW)* [4]. These requirements are applied to the waste packages that can be manufactured using the current range of standardised waste containers (as identified in the *Disposal System Specification Part B – Technical Specification* [2]) in the WPS that make up the WPS/300 Series of documents that form part of the WPSGD.

A number of UK Site License Companies (SLCs) will be required to manage a wide range of larger Plutonium Contaminated Material (PCM) waste items. Larger PCM items are defined as items where inclusion within existing PCM waste treatment processes is not considered practicable and the items are either:

- too large to be placed within existing RWM approved containers that are then placed in a Type B package without additional size reduction;
- will challenge existing disposal requirements unless further size reduction or conditioning is undertaken (e.g. voidage minimisation); or

- do not meet the criteria for Low Specific Activity (LSA)[4] or Surface Contaminated Object (SCO)[5] and so are not suitable for packaging within Type IP-2 packages such as 2 metre, 4 metre and 6 cubic metre concrete boxes.

These larger waste items potentially include crated gloveboxes and process equipment; wrapped sections of gloveboxes; processing equipment including vessels and tanks; and pipework.

It is noted that there are several potential benefits to SLCs and the Nuclear Decommissioning Authority (NDA) from considering the alternative options for larger PCM waste item management, including the following:

- Reducing worker risk exposure:

  Size reducing larger PCM waste items sufficiently to fit within containers smaller than a 3 cubic metre box may require extensive, long duration, 'hands on' pressurised suit operations. Regardless of the steps taken to minimise exposure to risk during such activities, this work remains inherently hazardous. The main risk from a safety perspective is considered to be from wounding and the absorption of Pu.

- Informing future decommissioning strategy and tactics:

  The development of alternative management options, including the use of larger containers, for larger PCM waste items would increase the options available to the planners of future decommissioning tasks. The removal of larger or whole plant items could significantly reduce the duration of those identified decommissioning activities.

  By increasing the options available to select the most appropriate size of waste container, decommissioning projects may be able to standardise future approaches to size reduction, tooling and waste handling, potentially avoiding issues relating to disposability of future larger PCM waste items and introducing further efficiencies.

This guidance is intended to assist waste packagers in achieving the safe and efficient packaging of larger PCM waste items, and in developing robust arguments regarding the performance of the resulting waste packages during transport and disposal.

1.1. Alignment with current guidance and specifications

There are existing waste specifications and guidance which are applicable to larger PCM waste items and should be consulted when developing a strategy for their management. It is not intended to replicate the existing guidance within this section, as it is best practice to design, demonstrate and manufacture a wasteform that meets all of the requirements and criteria specified within the wasteform specification. However, it is recognised that these requirements are inter-related and in specific circumstances an optimum waste packaging process may require the relaxation of one or more wasteform requirements to facilitate the production of a waste package which possesses acceptable overall performance. It is recognised that for larger PCM waste items there will be areas of the waste specifications which will be challenging to meet. The need for, and acceptability of, a relaxation of one or more wasteform performance requirements is determined as part of the disposability assessment. Guidance on this matter is best obtained on a case by case basis through early engagement with RWM in advance of a formal submission for the disposability

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[4] Low Specific Activity (LSA) is a material classification defined by the IAEA Transport Regulations as '*Radioactive material which by its nature has a limited specific activity (i.e. activity per unit mass of material), or radioactive material for which limits of estimated average specific activity apply*.' [1]
[5] A Surface Contaminated Object is a solid object which is not itself radioactive but which has radioactive material distributed on its surfaces. [1]

assessment of a packaging proposal. It should be noted that work is ongoing at RWM in a number of areas, including the development of acceptable ranges of voidage and quantities of decontamination agents. It is therefore intended that further iterations of this guidance can provide specific advice as this work is progressed.

Scotland's 2011 Higher Activity Radioactivity Waste Policy [5] is that long-term management of higher activity radioactive waste should be in near-surface facilities; however, throughout this report, guidance is provided on meeting requirements of a GDF. It should be considered that the requirements for disposal at a GDF will be broadly comparable to those for management in accordance with Scottish Higher Activity Policy.

1.1.1. RWM waste specification hierarchy

The RWM packaging specifications take the form of a structured hierarchy with each level having a specific purpose. The *Disposal System Specification Part B – Technical Specification* defines the requirements for all waste packages destined for geological disposal, and provides the basis for the definition of the Generic Specifications, which define the standards and specifications for waste packages containing specific categories of waste. The Generic Specifications are used to specify the requirements for the waste packages that could be manufactured using standardised designs of waste container, these being referred to as the WPS. The key specifications for the management of larger PCM waste items are listed below:

- Geological Disposal – Disposal System Specification Part B – Technical Specification [2];
- Generic specification for waste packages containing low heat generating wastes [4]; and
- Wasteform specification for waste packages containing low heat generating wastes [6].

Requirements contained within the Generic Specification for waste packages containing LHGW are separated into the following areas and need to be considered for the disposability of larger PCM waste items:

- requirements for waste containers;
- requirements for wasteforms;
- requirements for waste packages; and
- requirements for the manufacture and storage of waste packages.

Further guidance is provided on the wasteform within the Wasteform Specification for waste packages containing LHGW and the wasteform requirements are grouped under six headings:

- physical immobilisation;
- mechanical and physical properties;
- chemical containment;
- hazardous materials;
- gas generation; and
- wasteform evolution.

Depending upon the waste management strategy selected, further wasteform guidance is available in the form of:

- Guidance on the production of non-encapsulated wasteforms [7]; and

- Geological Disposal: Guidance on the production of encapsulated wasteforms [8].

1.1.2. Other guidance

There is existing regulatory [9] and industry [10] guidance associated with the management and storage of higher activity radioactive waste. Any waste management strategy developed for the management of larger PCM waste items should be in accordance with this guidance as far as is reasonably practicable.

Joint regulatory guidance on the management of higher activity radioactive waste on nuclear licensed sites [9] will provide the waste packager with the requirements associated with:

- the Regulatory process;
- integrated waste strategies;
- radioactive waste management cases (RWMC);
- waste minimisation, characterisation and segregation;
- waste conditioning and disposability;
- storage; and
- managing information and records relating to radioactive waste.

Industry guidance on the interim storage of Higher Activity Waste (HAW) [10] is specific to storage and provides more detail than the joint regulatory guidance on the management of higher activity radioactive waste [9] on the topic.

Following the available guidance will assist the waste packager to make an adequate RWMC and document the application of Best Available Techniques (BAT) / Best Practicable Means (BPM) and the application of the principles of As Low As Reasonably Practicable (ALARP) for the management of larger PCM waste items.

1.2. Application of BAT/BPM and ALARP

In identifying that an additional waste management strategy is required for the treatment of larger PCM waste items, and thus determining that a waste item is unsuitable for inclusion within an existing PCM waste treatment process, it is expected that the principles of BAT/BPM and ALARP are taken into consideration.

1.2.1. Best Available Techniques

In broad terms, "best available techniques" or “best practicable means” (in Scotland) means the latest stage of development of processes, facilities or methods of operation which is practicable and suitable to limit waste arisings and disposals. BAT/BPM applies throughout the lifetime of a process, from design to implementation, operation, maintenance and decommissioning [11].

A number of BAT/BPM considerations need to be taken into account when determining the viability of an existing PCM treatment route for a waste item. These considerations are included within the Radioactive Substances Regulation Environmental Principles (REPs) [12] and are discussed below:

- “Available techniques” means those techniques that have been developed on a scale that allows their implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the UK, as long as they are reasonably accessible to the operator.

- "Best" means the most effective in achieving a high general level of protection of the environment as a whole.
- "Techniques" includes everything that has a bearing on the benefits to be derived, for example:
    - the selection of a process to be used;
    - the design of facilities and systems;
    - the detailed implementation of facilities and systems; and
    - how it is managed, operated and maintained.
- Consideration of what are the best available techniques should be carried out on a case by case basis at each decision point where options exist.
- What is "*the best available technique*" is specific to the circumstances that exist at each specific decision point. Decisions should be informed by relevant guidance and good practice, wider experience and developments, e.g. at facilities elsewhere.
- A technique will not be BAT/BPM if its costs are grossly disproportionate to its environmental benefits. Costs include time, trouble, money and all other resources. All benefits and potential benefits should be taken into account.
- Where a statutory obligation requires stricter conditions and limits than those achievable by the use of BAT/BPM, then additional measures should be applied.
- If any benefit or reduction in detriment, however small, can be achieved using few or no additional resources then it should be secured.
- There is no threshold to dose, or any other detriment including environmental risk or contamination, below which no further consideration of what are the best available techniques is required.
- In determining BAT/BPM, an operator needs to achieve a balance across safety and environmental, societal and economic issues.

1.2.2. As Low As Reasonably Practicable

In identifying a waste management strategy for a larger PCM waste item there is a legal duty to reduce risk So Far As Is Reasonably Practicable (SFAIRP) which applies at all levels of risk. The Health and Safety Executive (HSE) and Office for Nuclear Regulation (ONR) guidance generally uses the term ALARP as a convenient means to express the legal duty to reduce risks SFAIRP. For assessment purposes the terms ALARP and SFAIRP are interchangeable and require the same tests to be applied. ALARP is also equivalent to the phrase 'as low as reasonably achievable' (ALARA) used in relation to ionising radiation exposure by other bodies nationally and internationally [13].

The starting point for demonstrating that risks are ALARP and safety is adequate is that the normal requirements of good practice in engineering, operation and safety management are met. This is a fundamental expectation for safety cases. The demonstration should also set out how risk assessments have been used to identify any weaknesses in the proposed facility design and operation, identify where improvements were considered and show that safety is not unduly reliant on a small set of particular safety features.

The development of standards defining relevant good practice often includes ALARP considerations, so in many cases meeting these standards will be sufficient to demonstrate that legal requirements have been satisfied. In other cases, for example where standards and relevant good practice are less evident or not fully applicable, or the demonstration of safety is complex, the onus is on the duty holder to implement measures to the point where it can demonstrate that the costs of any further measures would be grossly disproportionate to the reduction in risks achieved by their adoption.

Safety assessment principles (SAPs) are used in helping to judge whether reducing risks to ALARP is achieved. Priority should be given to achieving an overall balance of safety rather than satisfying each principle, or making an ALARP judgement against each principle. The principles themselves should be met SFAIRP.

1.3. Lifecycle radioactive waste management cases

A lifecycle RWMC should be used to document how the principles of BAT/BPM and ALARP have been applied to ensure that each stage of the waste item management is fully integrated with the lifetime plans for the waste and the site as a whole. The scope of an individual RWMC is a matter for the licensee. However, in deciding whether an RWMC covers a single waste stream or a group of waste streams the licensee should ensure that the totality of its RWMCs covers all higher activity radioactive waste on its site. As defined in the joint regulatory guidance on the management of higher activity radioactive waste [9], a lifecycle RWMC should indicate how the key elements of long-term safety and environmental performance will be delivered for the management of the waste streams covered. The RWMC for a larger PCM waste stream should cover all phases from its generation through conditioning, storage and up to removal from the site for eventual disposal. Collaboration with RWM is needed when developing the RWMC to reflect the full lifecycle up to the point of closure of a GDF. It should provide a complete account of the management of the waste stream that cannot necessarily be seen from examination of the individual plant safety cases and environmental documentation. At each stage the aim should be to ensure that radioactive waste is managed in a way that protects the health and interests of people and the integrity of the environment, both now and in the future, inspires public confidence and takes account of costs.

The long timescales involved may mean that the RWMC cannot cover all eventualities, and that some aspects may not yet be known. The RWMC should make it clear how such uncertainties are being dealt with and refer to a programme of work, where appropriate, that is designed to address any gaps in knowledge.

The RWMC will record and summarise key documents which will input into design considerations of future waste processing and storage facilities, ensuring that such facilities are compatible with the wastes they are intended to receive.

1.4. The assessment of packaging proposals

RWM has established the Disposability Assessment process [14] to support waste packagers in the development of plans to package higher activity wastes. Specifically the Disposability Assessment process is used by RWM to demonstrate that proposals to package waste would, if implemented, result in 'disposable' waste packages. In this context a disposable waste package is one that is compliant with all of the relevant regulations and safety cases for transport to and disposal in a GDF, and in line with regulatory expectations for the long term management of the waste [15].

The Disposability Assessment process also plays an important role in underpinning the generic *Disposal System Safety Case* (DSSC) [16] by providing confidence that the safety cases, which are based on generic assumptions regarding the wastes that are anticipated to be accommodated by a GDF, are compatible with the 'real' waste packages that are being manufactured. The performance of disposability assessments also helps us to demonstrate that the disposal concepts considered within the generic DSSC will be appropriate for the expected wastes as well as identifying wastes that could challenge current disposal concepts and allow early consideration of what changes may be required to these concepts to permit these wastes to be accommodated. If packaging proposals are endorsed by RWM, a Letter of Compliance (LoC) is issued, which may contain a number of action points required to be addressed before a final LoC is issued.

Guidance is available on the manner by which waste packagers should prepare submissions for the disposability assessment of packaging proposals [17].

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

- Background
- The wastes covered by this guidance
- Challenges presented by larger PCM waste items
- Development of lifecycle RWMCs
- Summary

2. Background

The *Implementing Geological Disposal* White Paper [18] sets out the UK Government's framework for the long-term management of the UK's higher activity waste, a key aspect of which is *'geological disposal, coupled with safe and secure interim storage'* of such waste. Whilst the precise manner in which geological disposal would be implemented in the UK (excluding Scotland) is not yet defined we envisage that any approach to long-term management of waste (including disposal) would comprise a number of distinct lifecycle stages which could include:

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

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

Prior to, and during the manufacture of a waste package, there are a number of additional lifecycle stages which are applicable to the management of larger PCM waste items. These lifecycle stages include:

- characterisation;
- pre-treatment;
- treatment;
- containerisation;
- conditioning; and
- interim storage

It is recognised that not all of these lifecycle stages are required, nor do they necessarily have to be undertaken in the order presented above. Figure 1 provides a generalised overview of the lifecycle of a larger PCM waste item and Table 1 provides a basic description of each lifecycle stage.

Figure 1: Generalised larger PCM waste item management lifecycle

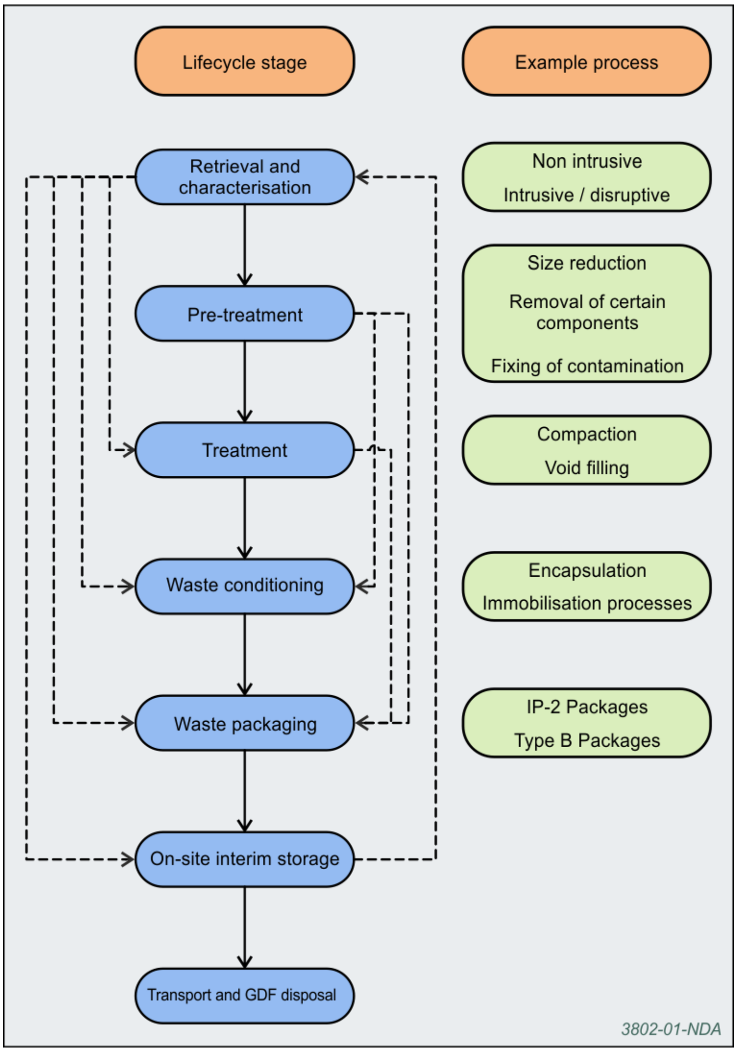

Table 1: Definition of waste management life cycle stages used in this guidance

Stage of Lifecycle	Description
Characterisation	For legacy waste items[6] there is a likelihood that characterisation data associated with the item is insufficient to adequately meet WPS requirements. Obtaining sufficient characterisation data could be achieved by a range of means including a review of historical records, non-intrusive characterisation and disruptive characterisation. For future arisings, the waste items may be well understood and so less additional characterisation may be required, or they offer the potential to undertake relatively simple characterisation due to being accessible.

[6] A "legacy waste item" refers to waste that has been previously created (often many years ago), before RWM guidance was available. These items were therefore produced to meet local requirements, often focused on storage rather than disposal, which were in place at the time.

Stage of Lifecycle	Description
Pre-treatment	Following characterisation, there may be a requirement to pre-treat the waste, which could require the selective removal of certain components and hazardous materials as outlined in the relevant WPS e.g. WPS/503/01 [7].
Treatment	Treatment of the waste is considered to include the minimisation of voids either through the introduction of additional material or through compaction. It is noted that for this guidance, it is assumed that the effects of any compaction will not allow the waste item to be accommodated in a container smaller in size than a 3 cubic metre box.
Containerisation	Containerisation is considered to include the placement of the larger waste item into a container, either for long term interim storage and disposal or for long term interim storage only. It may be considered that a waste item placed into a container to provide safe and passive storage during interim storage may require repackaging or overpacking in an additional container prior to disposal. One reason for doing this if the existing packaging is adequate for interim storage could be to keep options open for potential future waste treatment options that may become available.
Conditioning	Conditioning represents the application of techniques to produce the final wasteform and could include encapsulation or entombment.
Interim Storage	Interim storage is defined as the period involving storage of the containerised wasteform prior to disposal. Treatment and/or conditioning may be performed before, during or after interim storage.
Transport	Transport is defined as the movement of a disposable package from interim storage to a disposal facility (in most cases, this is assumed to be a GDF, unless characterisation enables diversion as low level waste (LLW).
Disposal	Disposal is defined as final emplacement of the waste package into a GDF or other disposal facility, without intent to retrieve.

2.1. Waste characterisation

Characterisation of waste items enables waste packagers to make informed decisions about the most appropriate disposal route and associated treatment and packaging methods available. Proper control of chemical and radiochemical parameters of radioactive waste across the entire life cycle, and careful testing of the quality of final wasteforms and waste packages, are principal components in any waste management strategy. Failures in control at any stage can result in significant consequences to subsequent stages of waste management. In some cases this may result in the generation of waste packages which are not compliant with the waste acceptance criteria (WAC) for on-site interim storage or the applicable WPS for transport and disposal [19].

In addition, an adequate description of the physical, chemical and radionuclide characteristics of any waste is required as part of a packaging proposal, in order to facilitate assessment. Further to this, during and subsequent to packaging, there is a requirement for waste packagers to produce and maintain adequate records relating to the contents and properties of all waste packages, and this necessitates an appropriate degree of characterisation.

2.2. Waste treatment and conditioning

A number of generic approaches to the packaging of LHGW, a category of HAW of which PCM is part, have been developed. This has included the definition of designs of waste container and the development of processes by which waste can be conditioned to produce a wasteform possessing such properties that will ensure the disposability of waste packages. A range of approaches to the conditioning of different waste types have been developed, which include:

- combination of the waste with an encapsulating medium (e.g. cement or polymer) to form an encapsulated wasteform;
- compaction of the waste in a sacrificial container and packaging the resulting product in a waste container by surrounding it with a suitable material to form an annular grouted wasteform;
- high temperature processing of the waste to form a monolithic vitrified wasteform; and
- use of more simple processes, such as size reduction and/or drying, to produce a non-encapsulated wasteform.

It is recognised that there may be instances where it could be appropriate to containerise some waste items without any further treatment or conditioning.

2.3 Waste packaging

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

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

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

It is the performance of the barrier(s) provided by the waste package that packaging specifications seek to address by defining requirements for waste packages which have been derived from the needs of their long-term management.

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

- For use with LSA ILW and LLW, such as would not generally require the extensive use of remote handling techniques, waste containers incorporating integral radiation shielding[7] can be used to create *shielded waste packages.* Such waste packages would generally be expected to be capable of being transported through the public domain without additional protection and would qualify as Type IP-2 transport packages in their own right.
- For higher activity ILW, such as would generally require the use of remote handling techniques, relatively thin-walled (i.e. a few mm) metal containers can be used to create *unshielded waste packages.* Because of their high external radiation dose rate, or requirements for the containment of their contents, such waste packages would be expected to be transported through the public domain in reusable shielded transport containers as Type B transport packages.
- For all types of ILW, thick-walled (i.e. many 10's of mm thick) waste containers can be used to provide both radiation shielding and physical containment of their contents, and to create *robust shielded waste packages.* Such waste packages are often capable of being stored, transported and disposed of without the need for remote handling techniques or for additional shielding or containment. It is noted that in some instances, additional protection, in the form of impact limiters for example, may be required. Depending on their specific design and radionuclide contents, robust shielded waste packages could be transported as either Type B or Type IP-2 transport packages.

2.4 Interim storage

For HAW, in England and Wales, waste packages need to meet the requirements for all waste packages destined for geological disposal as set out in the WPSGD. The LoC process provides assessment against these requirements noting that WAC criteria are yet to be established.

In Scotland, waste packages continue to be assessed through the LoC process. The Scottish Environmental Protection Agency (SEPA) currently advises that any waste suitable for disposal will also be suitable for long-term storage in accordance with Scottish Government HAW policy. In Scotland, the LoC process is kept under review which will allow consideration of whether there needs to be further changes to the process to recognise that some wastes are destined for near-surface disposal [5].

The LoC process can be considered a risk management approach. Following the LoC assessment process, and utilising the supporting guidance, should greatly reduce the risk of packages requiring rework during interim storage.

The Store Operator should maintain a continuing dialogue with RWM, especially when: establishing and updating store WAC, updating RWMCs, and developing store safety cases. Engagement with RWM should occur at an early stage of the development of the storage system, and with any emergent disposability issues.

2.5 The transport of waste packages

Whilst the geographical location for a GDF has not yet been identified it is acknowledged that some or all of the waste packages manufactured in the UK will have to be transported, through the public domain, from their site of arising to the GDF. The generic Transport Safety Case [20] assumes that all waste packages will be transported. These transport operations will be subject to a number of national and international regulations the most

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

significant of these being the International Atomic Energy Agency (IAEA) *Regulations for the Safe Transport of Radioactive Material*[8] [21]. Regulatory control in the UK for road and rail transport is in accordance with the Carriage of Dangerous Goods and Use of Transportable Pressure Equipment Regulations, which incorporate the requirements of the IAEA Transport Regulations.

The IAEA Transport Regulations apply to the transport of many categories of radioactive material including wastes with a wide range of specific activities. To ensure a proportionate approach in maintaining the safety of such materials, a number of categories of 'transport package[9]' are defined, including:

- Type B packages – These packages are intended for transport of high hazard radiological materials. They provide an appropriate level of containment in the event of specified conditions, such as an engulfing fire of a specified temperature and duration or impact of a specified severity. Type B packages include the 500 litre drum and the 3 cubic metre box; and
- Industrial Packages – These packages are used to transport material comprising Low Specific Activity (LSA) or Surface Contaminated Object (SCO). IPs are defined at the levels (IP-1, IP-2 and IP-3) based on the allowed content. The RWM 2 metre and 4 metre boxes are examples of an IP-2 package. The need for IP-1 and IP-3 transport packages has not been identified at this stage.

It is assumed in the Generic Specification for waste packages containing LHGW [4] that only these types of transport packages will be used for the transport of waste packages containing wastes such as ILW.

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

By contrast, no such limits are placed on the contents of Type B transport packages as different requirements of the package are specified in the IAEA Transport Regulations both during normal and accident conditions. As an example, the IAEA Transport Regulations specify a containment criterion for a Type B transport package which, when subjected to testing, is required to demonstrate the ability to withstand accident conditions during transport whilst retaining its contents.

The fundamental principle of the IAEA Transport Regulations is that safety is to be ensured by the design of the containers and by limits imposed on their contents, regardless of how the material is transported. These limits and regimes are used as part of the process for setting limits and performance standards for waste packages in the relevant packaging

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[8] Referred to hereinafter as the 'IAEA Transport Regulations'.

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

specifications and, in some cases, they are the most bounding values for all stages of the long-term management of those waste packages.

2.6. The disposal of waste packages in a GDF

For a waste package to be deemed 'disposable' it must be both physically compatible with the systems defined for transport and a GDF, and with the assumptions that underpin the safety cases for transport and the operational and post-closure periods of a GDF. The design of a GDF, which will be strongly influenced by the geological environment in which it is constructed, will therefore place significant constraints on the properties and performance of waste packages.

A wide range of different geological environments that could be suitable for hosting a GDF for HAW exist in the UK. However, at the current stage in the Managing Radioactive Waste Safely process, no site for a GDF has been selected and so the actual design of a GDF has not been defined. Therefore, the packaging requirements defined in the *Disposal System Specification Part B – Technical Specification* have been defined in such a manner that they bound a sufficiently representative range of GDF designs.

3. The wastes covered by this guidance

This guidance covers larger PCM waste items where it may not be practicable for inclusion within existing PCM waste treatment processes and they cannot be placed into existing disposal containers smaller than a 3 cubic metre box without challenging existing disposal requirements or requiring a large degree of size reduction.

The definition of PCM varies across the UK SLCs, but the technical specification for this guidance defines PCM[10] as:

"Wastes containing plutonium material that is not practicable to recover, with radioactivity levels exceeding the upper boundaries for LLW, but which do not require self heating to be taken into account in the design of the storage and disposal equipment."

The current PCM waste management strategies across SLCs are as follows:

Sellafield Ltd (SL): For operational PCM wastes the baseline treatment process involves placement of the waste in 200 litre drums which are then supercompacted in the Waste Treatment Complex (WTC). The supercompacted pucks are then placed into a stainless steel 500 litre drum using guide rods to centralise and support the pucks prior to grouting. Grout is added to fill the annular space between the drum and liner, and to surround the pucks.

For larger PCM waste items it is understood that a crate breakdown facility is proposed within the current SL Lifetime Plan [22] which is planned to support the size reduction of the crates / larger items. Segmented waste items would then be placed within a waste container ahead of grout encapsulation.

SL is currently evaluating the use of alternative PCM treatment approaches based around the application of a range of thermal technologies for PCM waste stored in 200 litre drums. However, SL has also expressed an interest in placing legacy larger PCM waste items, known as crates, directly into a container with only partial encapsulation of the waste if required. The containers proposed for the PCM crates are either a Gemini Waste Box (GWB) or 4 metre or 2 metre boxes depending on their compatibility. Preliminary work undertaken by RWM and SL relating to these proposals has identified key focus areas for

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[10] 'PCM' is the term used throughout the guidance, but that could be taken to encompass other wastes with similar characteristics (relatively high fissile content, low dose rates/contact handleable, uranium and/or transuranic content).

further specific work on these crated waste items, which have been used to inform the topics covered within this guidance.

Dounreay Site Restoration Ltd (DSRL): Following characterisation of Contact Handled Intermediate Level Waste (CHILW) PCM 200 litre drums in storage, most will be supercompacted in a new or modified facility. The supercompacted pucks will be placed in a 500 litre drum and grouted. Any drums unsuitable for supercompaction due to their contents will be managed separately before emplacement in a 500 litre drum and grouted. The drums will subsequently be stored alongside other 500 litre drums within a shielded store [23].

Atomic Weapons Establishment (AWE): Operational and historic decommissioning PCM waste is placed in 200 litre drums. AWE are currently undertaking a characterisation exercise in an attempt to re-categorise a portion of the PCM waste in interim storage as LLW, while considering sending significant volumes of ILW to Sellafield for compaction in their WTC. In relation to the future management of larger PCM waste items, AWE has been working with RWM to develop a solution for packaging the legacy hydrodynamic vessels with a view to ultimate disposal in a GDF as ILW. The proposals that are being worked up by AWE are based on entombment of the legacy vessels in square cornered 3 cubic metre boxes. The void between the vessel and box walls would be infilled with cementitious grout. The void within the vessels would remain unencapsulated. AWE has received Conceptual stage endorsement for these proposals from RWM in 2010 on the grounds that package performance requirements for safe handling and transport would be achieved through a combination of the high integrity of the hydrodynamic vessel coupled with the additional protection offered by the 3 cubic metre box and surrounding cement grout [24].

Generic Baseline: For the purposes of this guidance, a generic baseline for PCM waste management has been proposed, which is based on SL's existing PCM management approach for 200 litre drums, outlined above.

3.1. Larger PCM waste items and their origins

A larger PCM waste item is defined within this guidance as a PCM item which cannot fit into a 3 cubic metre box without challenging disposal requirements or requiring a form of size reduction and for which size reduction into 200 litre drums is not deemed practicable by the waste packager. Larger PCM waste items pose a range of unique challenges which are not incurred when managing standard PCM waste items. The main areas of challenge are associated with the physical characteristics of the waste item (i.e. the mass and dimensions), the characterisation data available for the waste item and the fissile mass associated with the item.

It is expected that all larger PCM waste items will have been assessed to determine whether they can be incorporated into the baseline PCM management strategy or packaged into other suitable containers; however, it is accepted that there may be reasons (e.g. need to reduce worker risk exposure and to reduce the duration of future decommissioning activities, as identified in Section 1) why size reduction, compaction and subsequent encapsulation in either 500 litre drums or 3 cubic metre boxes is not considered to be a practicable approach for some items of waste.

The option of developing a large waste container (LWC) and associated large waste transport container (LWTC) is being explored and is discussed in more detail in Section 4.

The range of larger PCM waste items that will need to be managed include items currently stored on sites and items that will be generated during future decommissioning activities i.e. legacy and future arisings respectively. Representative waste items have been identified through consultation with the SLCs [25] and have been classified in four main categories which are considered to be sufficiently representative of the waste items likely to be managed as larger PCM waste items. Summary information on the representative waste items can be found in Table 2.

Table 2: Representative larger PCM waste items

Item	Description	Approximate Size (m)
Crated Waste	GWB which fits into a LWC	Crate: 2.16 x 1.34 x 1.31 Contents: examples include disassembled gloveboxes and components.
	Crated waste (with contents) which does not fit into LWC.	Crate: greater than internal dimensions of LWC (2.96 x 1.61 x 2.01[11]) Contents: examples include cyclone separators and plutonium nitrate pumping cabinets.
Glovebox	Whole gloveboxes	A wide range of sizes, such that an average would be skewed by outliers. However, there is a reasonable population of gloveboxes with approximate dimensions 1 × 2.5 × 3.1
	Sections/panels of gloveboxes, mostly stainless steel; includes windows.	2 × 0.1 × 1.6
Pipework	Variable sections of pipework, the majority of which are too long to fit within a LWC.	3.9 × 0.2 (thickness 0.003)
Processing Equipment	Vessel and tanks containing a heel.	1.53 × 1.4 × 3.38

Legacy items

A number of larger PCM waste items have already been generated and are in interim storage pending identification of a suitable waste management route. Legacy wastes may pose different challenges to future arisings having originated over a number of decades and the information and records describing the waste items in the crates varies significantly between items which are well understood and those where there is very little characterisation data.

At the time of generation, these legacy items were not incorporated into the PCM waste management baseline (i.e. 200 litre drums), predominantly due to either the activity of the waste item and/or the physical characteristics making it particularly difficult to size reduce within constraints such as engineering functionality or time. Legacy larger PCM waste items arising from historical operational activities were generally placed in crates because the operational facilities were not designed for decommissioning activities such as size reduction. If there was a requirement to remove larger PCM equipment during operations, placing the item within a crate was often seen as a viable option. Further legacy wastes

[11] LWC dimensions are based on the initial preliminary conceptual design schemes and are therefore subject to change. No allowance has been made for manufacturing tolerances or operational clearance required for contents loading operations.

arose from decommissioning activities where, although designed for decommissioning, the project's options were often constrained, requiring items that were difficult to incorporate into the baseline PCM waste management strategy being simply removed from facilities and crated. The PCM retrieval activities from the Low Level Waste Repository (LLWR) also resulted in legacy wastes being placed in crates.

4. Challenges presented by larger PCM waste items

Larger PCM waste items can present a series of challenges to the waste packager in meeting disposal requirements. It is recognised that the requirements and aspirations of the waste packagers and RWM may vary at different stages of the waste management lifecycle noting that not all stages are compulsory and the stages do not necessarily have to be done sequentially. This section identifies specific areas of challenge and collates relevant guidance for each topic, then discusses the concept of balance of risk in developing lifecycle waste management cases for larger PCM waste items.

4.1. Specific areas of interest for packaging larger PCM waste items

The areas which are likely to present a challenge to waste packagers in meeting the requirements for transport and disposal in a GDF are set out in this sub-section.

Knowledge and understanding of the waste item

Quantification of the radionuclide inventory of some larger PCM waste items by direct measurement may be rendered difficult by the nature of the item. For example, it may be considered impracticable to sample the waste item in order to determine the radionuclide inventory, where such an operation may compromise the beneficial properties provided by the intact item. Further, such operations are likely to involve risks to operator safety, additional operator dose uptake and cost. It is recognised that larger PCM waste items may contain americium-241, which due to the gamma ray by-product of alpha decay (60keV) can result in a significant dose uptake to operators if it is not shielded.

Because of the potential difficulties associated with the direct determination of radionuclide inventory, it may be preferable to utilise operational records relating to a specific item or plant in order to derive a suitable radionuclide inventory where these records can demonstrate compliance with relevant legislation and safety cases. This approach is likely to be particularly attractive where radionuclides are difficult to measure but it is also noted that if further characterisation is required, reviewing historical records may also be useful in judging the quality of radionuclide assay obtained from characterisation techniques.

For legacy items, operational records alone may be limited in terms of their usefulness in determining a radionuclide inventory for a given waste item; however, for future arisings, an opportunity exists to ensure that information about the waste item is well understood and so additional characterisation may not be required.

Solely relying on undertaking minimal characterisation and other non-intrusive work to demonstrate that transport and disposability requirements can be met may prove to be challenging to waste packagers, particularly for higher activity items. However, these approaches may be attractive to the waste packagers as they will minimise up front health and safety risks to workers, and may potentially provide financial savings. The converse is true for options involving intrusive/disruptive characterisation work and treatment activities, where increased confidence in meeting requirements for transport and disposal is achieved at the expense of the need to manage/accept higher health and safety risks and costs at the front end of the lifecycle, during on-site operations. It is recognised that any front end activities undertaken by the SLC would still be undertaken in a safe and legal manner, but the management of additional risks may be undesirable when assessed for BAT/BPM and ALARP. Where uncertainty remains despite best practicable characterisation efforts, in some cases waste packagers and RWM may need to consider the balance of risks in detail through an appropriate process carried out with regular consultation in order to agree the BAT/BPM and ALARP approach to managing larger PCM waste items.

Demonstrating and meeting safe fissile mass limits

During storage, transport and the operational period of a GDF (i.e. up to vault backfilling), a criticality could lead to damage to the waste packages, spread of contamination and the exposure of persons to radiation both during the event and in the remediation of the damaged waste packages and contaminated areas. In these periods, the potential for a criticality is avoided, in individual packages and assemblies of packages, by control achieved through waste package design and, in particular, control of the quantities of fissile material that are permitted in waste packages [26].

For transport of a package containing fissile material, RWM has to assess the fissile mass provided by the waste packager against deterministic limits set out in the IAEA Transport Regulations as enacted in UK law [21]. These limits are prescriptive and if a credible range cannot be demonstrated by the waste packager, the worst possible case has to be assumed for all parameters and combinations of parameters. In this scenario, complex modelling is required and it will be challenging to make a transport safety case for waste packages with unknown hold-up. The challenge of making a transport safety case is even greater if the waste is not encapsulated.

For disposal at a GDF, two separate assessments of the criticality safety of waste packages are required, which consider the periods before and after deterioration of the waste packages that could lead to a loss of containment and the redistribution of fissile material. The first of these two periods corresponds to the GDF operation period and the period immediately following disposal vault backfilling, the second to the GDF post-closure period), the latter period being generally the most bounding for the allowable fissile contents of waste packages [27].

From a criticality safety viewpoint, during the operational phase of a GDF the waste packages are now in arrays and neutron interaction between them will have to be considered. Also, the movement of waste packages in the facility means that the possibility and consequences of impact accidents have to be considered. Criticality requirements for the operational phase of a GDF are not normally the most constraining but will still need to be assessed as it is possible that a criticality case is made for transport on the basis of a single package, whereas an array of packages may be emplaced within a disposal vault [27].

For the post-closure phase of a GDF, once the barriers provided by the waste packages begin to degrade the contents may become mobilized by groundwater. In contrast to preceding periods of the management of the waste packages, criticality safety cannot now readily be demonstrated through assessment of the protection offered by engineered measures and the restrictions of the fissile material contents of waste packages in preventing criticality. In the post-closure criticality assessment there will necessarily be more reliance on probabilistic arguments, in particular that the combined likelihood and consequence of criticality in this period is very low [27]. In general it is considered unlikely that a criticality would occur because [28]:

- a larger item is likely to be packaged as a single item;
- the fissile material will be emplaced in a GDF in a sub-critical configuration with multiple engineered barriers in place to retard the effects of processes that might lead to significant relocation of fissile material;
- many of the anticipated changes in the arrangement of waste packages in this environment following closure might be expected to take the system further subcritical;

- for ILW, the fissile material is well spread out, the total fissile content of 13.5 tonnes being dispersed through ~470,000 m^3 of waste packaging materials, at concentrations well below critical values; and
- the majority of the ILW within a GDF is/will be encapsulated in cement, and ILW disposal concepts are based on cementitious backfill, the chemical and physical properties of which hinder movement of fissile material.

It is recognised that further work may be required to demonstrate that a rapid transient criticality event is incredible for packages containing significant plutonium if these waste packages are not due to be encapsulated.

Furthermore, the consequences of a post-closure phase criticality are considered low because [29]:

- rapid transient criticality could only occur for a narrow range of hypothetical conditions, and such a criticality is not considered to be credible after about 100,000 years post-closure, due to decay of ^{239}Pu to ^{235}U;
- for a Quasi Steady State criticality, the physical consequences are highly localised and would not be expected to affect the surrounding geosphere, and therefore would not significantly impact on overall risk;
- direct radiation from the criticality event would be shielded by the surrounding rocks and materials. Unlike during the transport or operational phases of the GDF there will be no direct risk posed to operators or members of the public;
- for a Quasi Steady State criticality, the calculated temperature rise and power are less than 300 °C locally and a few kilowatts, irrespective of whether the underlying scenario is accumulation, stack slumping or in-package flooding;
- even if they do occur, criticality events are likely to affect only a limited part (of the order of tens of cubic metres) of a GDF storage volume;
- criticality events involving very large amounts of fissile material might have a significant impact on a small fraction of a GDF and the engineered barrier system, but these events are very unlikely and could only occur a long time (hundreds of thousands of years) after closure where the radioactive inventory will have decayed to much lower levels. Therefore their effect on the overall risk would be small; and
- the backfill/buffer and geological environment will still act to isolate the radioactive waste from the surface environment.

RWM (and its predecessor organisations) has worked since the early 1990s on developing a capability to understand and to be able to demonstrate the post-closure criticality safety of a GDF. The conclusion drawn from the totality of this work was that, for all HAW disposed of in three illustrative host rocks, post-closure criticality would be a low likelihood and a low-consequence event [30].

RWM's research in support of waste package criticality safety has focussed on ILW and LLW packages and this has led to the derivation of a hierarchy of fissile material limits for ILW/LLW and some depleted, natural and low-enriched uranium packages. As one moves up this hierarchy, credit is taken for increasing knowledge of the specific waste stream, and its characteristics, in deriving fissile material limits [27]. Packaging to these increased fissile material limits can only be justified if there is a demonstration of the waste package understanding necessary to ensure compliance with requirements on package criticality controls.

The first level is a general screening level (GSL) of 50 g ^{239}Pu (or its equivalent). The general criticality safety assessment [31] is based on wastes being packaged with limits on the content of graphite (1 kg), beryllium and deuterium (both 100 g); a slightly lower fissile material limit applies if an unlimited amount of graphite is possible. Package-scale scenarios have been defined to cover the operational and post-closure periods. These package-scale scenarios were deterministically calculated assuming optimum (in terms of achieving criticality) geometries and concentrations for the accumulation and interaction of pure fissile materials, resulting in a very robust GSL that can be applied to waste packages containing any fissile radionuclides.

The next level is represented by the generic Criticality Safety Assessments (gCSAs). Four have been produced for common categories of fissile HAW packaged in 500 litre drums, 3 cubic metre boxes and 3 cubic metre drums. One of the categories of fissile HAW for which a gCSA has been produced is separated Pu [32]. Although it applies to standard waste packages, it may provide some relevant guidance for the packaging of larger PCM waste items in alternative waste containers. The gCSAs recognise generically (to ensure wide coverage) the isotopic variations of uranium and plutonium, which results in significantly higher fissile material limits for packages containing natural and low-enriched uranium wastes.

The gCSAs deterministically derive limits for transport, operations and the post-closure phase. Conditions during the transport and operational phases are more constrained and defined than in the post-closure phase as the GDF will continue to evolve over such long timescales. The approach to assessing criticality safety during the transport phase is also more prescriptive than for the operational phase. Therefore, whilst similar processes are assessed in all three phases, scenarios for each of the three phases are developed separately [30]. In most cases, the transport phase fissile material limits are more restrictive than the operationally-derived fissile material limits, which is unsurprising given the prescriptive and conservative nature of the IAEA Transport Regulations. A new package envelope approach has been developed for post-closure criticality safety assessment (Section 3.4.3 of [30]) that may be applicable to the small proportion of waste packages for which the post-closure fissile material limits are constraining because, over long timescales, conservative assumptions need to be made.

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

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

A key area in demonstrating that the package meets the transport and disposal requirements is an understanding of the uncertainties used in determining the fissile mass present. For Legacy Items, demonstrating the package is below the SFM may prove to be challenging and applying conservatisms to uncertainties may be attractive to waste packagers as these conservatisms may still comply with the SFM limit and allow crude characterisation based on large uncertainties. Applying conservatisms could minimise the upfront health and safety risks to the operators associated with the reduced scope of characterisation and potentially minimise costs. To resolve uncertainties and satisfy transport and disposal requirements, in-depth characterisation may be required, which would result in a significant increase in risks and costs to the waste packagers. A pragmatic approach to determining the fissile mass within an individual package and the SFM for a range of wasteforms and waste containers is required and early engagement with RWM is considered necessary where uncertainties exist surrounding the establishment of the fissile mass within a waste item.

Voidage

Voidage in a wasteform reduces confidence in the predictability of performance under normal and accident conditions and may undermine steps taken to engineer particular properties of the wasteform or address specific performance criteria for the GDF [33]. Examples of the possible adverse effects of voidage include [7]:

- local corrosion leading to the presence of mobile particles with a significant radionuclide content;
- prevention or hindrance of the chemical conditioning of key constituents of the waste;
- reduction in wasteform and waste package strength compared with expected values;
- accumulation of flammable/explosive gas;
- generation of other hazardous materials (e.g. metal hydrides); and
- long-term slumping/subsidence in a GDF.

The actual consequences of voidage, in particular the magnitude of any related hazards, will depend on the nature of waste, the wasteform and the container design. Accordingly, minimisation of voidage is considered to be best practice and adds confidence to packaging process control and the predictability of waste package performance. Some larger PCM waste items, for example gloveboxes or vessels, will pose a particular challenge due to the presence of significant voidage. As previously noted, current PCM management techniques involve compaction of the waste to remove void space; for example, through supercompaction in the WTC at SL.

By consideration of the above list of adverse effects, it may be possible to argue that the presence of some voidage does not compromise the overall performance of the waste package or disposal system.

Recent work [33] on voidage has proposed that in order to give confidence that damage to the GDF backfill will be limited and that the risk of significant damage to the host rock is minimised, an open void screening level of ~5% is introduced for individual waste packages. Waste packages containing up to 5% void space would be acceptable without further justification, allowing waste packagers to demonstrate that the requirement of 'voidage minimisation' has, in practice, been met. This value is consistent with the levels of void space in many existing waste packages. Above this value, waste packagers would have to make the case for higher levels of void space, and the implications for post-closure performance of the GDF would have to be assessed by RWM.

Voidage can be reduced through encapsulation; however, if encapsulation is not to be part of the conditioning process and the presence of voidage is an issue, it may be that use of a suitable material (i.e. glass or polymer beads, dried sand etc.) as a void filler would provide adequate waste package performance [7]. Any such use of void fillers would need to be supported by a demonstration that the proposed infilling process was effective at reducing voidage to an adequate degree and was deemed to be BAT/BPM.

If encapsulation is not to be part of a conditioning process the waste will be required to have a number of characteristics which will make it more capable of satisfying the requirements specified for the wasteform by the relevant packaging specification [7]. In summary, such wastes should be [7]:

- bulk non-friable solids, relatively free of particulate material;
- relatively free of non-fixed surface contamination, or capable of easy decontamination before placement in a final container;

- dry, or such that any free liquid can be easily removed before placement in a final container;
- of sufficient compressive strength so that it is not readily fractured when subjected to the loads that would be expected under normal conditions during transport or disposal;
- under accident conditions, of a particle size distribution and corresponding release fraction that is understood and can be used to demonstrate that the wasteform and container meet the relevant requirements;
- resistant to atmospheric corrosion; and
- chemically inert (i.e. not combustible, pyrophoric or exhibiting reactive or exothermic behaviour), and chemically compatible with the proposed waste container material.

Free liquids

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

- an increase in the mobility of radionuclides or toxic species in solution or suspension, potentially resulting in the spread of contamination;
- an increase in the quantity of radioactive material released during normal and accident (i.e. impact and fire) conditions;
- an increase in the potential for chemical interaction between different waste components or between waste components and packaging;
- increased corrosion of components within the wasteform;
- increased inhomogeneity within the wasteform;
- increased microbial activity within the wasteform; and
- a reduction of the predictability of wasteform performance under normal and accident conditions.

The presence of free liquids in a non-encapsulated wasteform would exacerbate such problems and it would be necessary to show that particular attention would be given to their removal. It is recognised that the demonstration of the absence of free liquids may not be a simple exercise in larger PCM waste items. However, the minimisation or elimination of free liquids should be regarded as best practice. All sources of free liquids relevant to the waste under consideration should be identified and, ideally, the absence of free liquids argued or demonstrated practically.

The presence of significant quantities of free liquid in a waste would generally suggest that such a waste is not suitable for non-encapsulation, as often the best solution to such a property is the mixing of the liquid with a binding agent such as cement. For wastes containing more limited quantities of free liquid, the use of an inorganic sorbent or desiccant may be suitable (noting that use of an organic sorbent was a potential cause of radiological releases from a drum within the Waste Isolation Pilot Plant (WIPP) in the US in February 2014 [34]). If such a material is used, its long term performance, particularly under the influence of radiation, should be known to prevent the possibility of any absorbed liquid becoming desorbed after packaging.

Free liquid could be present in a number of larger items, especially those with voids and associated with process equipment such as pipework or vessels which may contain residual acidic liquors. Acidic liquor has been found in a small number of legacy PCM drums at the LLWR with the liquor needing to be neutralised and immobilised prior to disposal [35]. The removal of any free liquids within larger PCM waste items is likely to prove challenging, but relevant experience for their management may be obtained from the WTC at Sellafield, where liquids arising from the compacted pucks are collected in bottles, neutralised, grouted and compacted [36]. .

For easily accessible waste items, free liquids can sometimes be effectively eliminated by relatively simple pre-treatment of the waste prior to packaging (e.g. by settling and draining) or by more aggressive drying techniques such as heating and/or the application of reduced pressure to encourage evaporation. Sealed vessels should be perforated and crimping of pipework during cutting should be avoided to reduce the possibility of trapped liquids. It is recognised that undertaking liquor removal in larger PCM waste items will present greater challenges.

Immobilisation of radionuclides and particulates

To ensure that the performance of a waste package is acceptable during all stages in its long-term management, adequate immobilisation of radionuclides and other hazardous materials associated with the waste must be achieved by the wasteform. Immobilisation may be deemed to be ‘acceptable’ from a disposability perspective if the release of radionuclides from a waste package under normal and accident conditions during interim storage, transport and the operational period of a GDF is ALARP and does not result in radiation doses that exceed the limits specified by the safety cases for each of those periods. For standard PCM waste arisings, immobilisation is provided by supercompaction of the 200 litre drums and placement into a 500 litre drum, which is subsequently filled with a cementitious grout.

In the absence of intimate encapsulation, adequate immobilisation will have to be achieved by other means. In the case of a waste package containing a non-encapsulated wasteform it is the provision of physical containment by the waste package as a whole that will determine whether the wasteform is providing adequate immobilisation. Adequate immobilisation of radionuclides by the waste package can be provided by one or more of the following:

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

It is recognised that tie-down coatings have been explored by SLCs as a means of fixing contamination; and due to their longevity and organic nature and the resulting perceived potential impact on disposal, their use has often been avoided in the past [37]. However, subsequent work has been undertaken by RWM in conjunction with SLCS on strippable coatings, paints and fixatives which has identified a number of applications which may be suitable for fixing contamination [38]. Guidance was then developed on the disposability of waste packages containing decontamination agents [39], which summarises the potential threats and mitigations that could be used in developing a packaging proposal for wastes containing these chemicals for assessment by RWM.

The provision of physical containment of a non-encapsulated wasteform (e.g. a grout annulus) can provide additional containment of the radionuclides and particulate within the waste package, provided that the integrity of the annulus can be demonstrated for the required timescale. In this way, the need to demonstrate immobilisation within the waste itself may be removed.

The use of a robust shielded waste container could also remove many of the requirements on the wasteform and could significantly reduce the need to immobilise radionuclides and particulate in a non-encapsulated wasteform. However, the wasteform in such a container will still need to provide a degree of immobilisation to ensure adequate package performance, particularly under accident conditions.

Most wastes that are amenable to non-encapsulation will not have characteristics that result in their associated radionuclides being ‘mobile’. Such wastes would not include components such as particulate matter or liquids at the time of packaging. It is also important that the evolution of wastes (e.g. corrosion) does not result in the creation of such components over the timescale when immobilisation is required. For wastes such as PCM, which contain radionuclides with half-lives of greater than a few decades, this should extend until at least the end of the GDF operational period. In the generic WPS for waste packages containing LHGW this period is quantified as 150 years following waste package manufacture, to ensure adequate wasteform performance during transport and the GDF operational period [4].

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

The evidence required to demonstrate adequate immobilisation could include the following (Section 5.1.1 of [8]):

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

The evidence for adequate immobilisation provided by a wasteform design should be submitted in a staged approach as required by the Disposability Assessment process [14].

Chemical containment and hazardous materials

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

Such materials may exist at the time of packaging, and further hazardous materials (e.g. organic molecules and gases) may be produced from the degradation of the waste, the materials used for conditioning and packaging, or by reactions between them. The transport and handling of all such materials will be subject to the appropriate regulations as well as a general duty of care. Consequently, the potential presence or generation of such materials will have to be taken into account during the design of a waste package.

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

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

a) Oxidising materials

Oxidising materials are defined as those which exhibit highly exothermic reactions, or form unstable compounds, when in contact with other substances, particularly flammable substances.

Oxidation reactions may produce gases which could increase the pressure within the wasteform and/or waste package. The presence of oxidising materials increases the potential for fire, as they provide a source of oxygen to combustible material.

The presence of both types of material in the same waste may therefore compromise the benefits of a conditioning process that seeks to render the waste non-combustible by excluding atmospheric oxygen. Examples of oxidising materials include peroxides, chlorates and nitrates.

b) Flammable materials

Flammability hazards are subdivided into two broad categories: highly flammable and flammable. Highly flammable materials include the following:

- liquids having a fire point below 21°C (i.e. for which the vapours will burn for at least 5 seconds after ignition by an open flame);
- gaseous substances that are flammable in air at room temperature; and
- substances, such as metal carbides and hydrides, which in contact with damp air or water evolve highly flammable gases.

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

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

c) Sealed containers

Although pressurised containers (e.g. gas cylinders, aerosol cans, compressed air system components) are not likely to be encountered as part of a larger PCM waste item, sealed containers may be present within the item (e.g. trash cans used within a glovebox). Sealed containers that were not pressurised at the time of packaging could nonetheless become pressurised over time as a result of gas generation due to corrosion, radioactive decay and/or radiolysis. The presence of sealed containers in wasteforms could also compromise the requirement to minimise voidage.

The presence of sealed and/or pressurised containers within a wasteform would represent a significant increase in risk of damage to the wasteform and breaching of the waste package.

Release of the stored energy by catastrophic failure of a pressurised container could result in a breach of the waste container and dispersal of the waste package contents. During handling operations associated with interim storage and transport this would represent a risk of injury, increased dose to workers, and possible damage to safety systems and other packages. Less energetic failures could result in localised damage to the wasteform and waste container, and an associated loss of integrity. Additional hazards could also be presented by the released contents of the container if they are hazardous in their own right.

How can adequate consideration and treatment of hazardous materials be demonstrated?

The nature and magnitude of the hazard presented by a specific material will depend on the general nature of the waste, the form of the wasteform and conditioning processes adopted. During the development of a packaging proposal the waste packager should demonstrate that any identified hazardous materials will be removed from the waste or their hazardous properties neutralised.

A range of techniques could be applied to manage any hazardous aspects of a larger PCM waste item, either as part of a selective conditioning technique or by removal of the hazardous components of the waste item. Appendix E of the Optimised Management of Orphan Wastes report [40] presents a range of potential treatment technologies which may be suitable which include chemical, high temperature, immobilisation and physical techniques.

Further information on the management and disposability of hazardous materials

The IAEA has produced a report [41] which may be of use to waste packagers where the waste contains toxic properties or hazardous characteristics. The report has reviewed available information and outlined the management options for problematic decommissioning waste and material, which are different from those for waste generated during the normal operation of nuclear facilities. Specifically, the report covers waste and material that has been identified as being conventionally hazardous and requires special attention because of their specific toxic properties or other hazardous characteristics.

As noted above, more information on the management of such wastes can be found in a summary of previous work on problematic waste [42]. If a hazardous section of a larger PCM item is removed to facilitate disposal, the removed section may be suitable for disposal as LLW; in which case the LLWR LLW Problematic Waste Technology Optioneering Summary Report should be consulted [43].

It is recognised that larger PCM waste items could include a range of hazardous materials, e.g. in the form of oils or lead; the presence of which must also be considered in terms of their disposability at a GDF. Following the adoption of the Groundwater Daughter Directive into UK legislation in the Environmental Permitting (England and Wales) Regulations 2010 (EPR10) [44], RWM is considering the protection of groundwater from the introduction of (non-radioactive) hazardous substances and non-hazardous pollutants (collectively referred to as non-radiological pollutants[12]) in the post-closure phase of a GDF. RWM has developed an Implementation Plan to improve our understanding of the inventory of non-radiological pollutants and of the implications of these for our safety cases. Ongoing work includes development of a total system model (TSM), together with the generation of appropriate data to facilitate calculation of the concentration of non-radiological pollutants at defined compliance points. Application of the TSM to a set of assessment scenarios will be tested for potential use as a screening tool for non-radiological pollutants as part of RWM’s Disposability Assessment Process.

Availability of containers

For wastes containing fissile material, it is expected that, in general, larger PCM waste items will require to be packaged within an unshielded ILW (U-ILW) container that would be overpacked for transport as a Type B package. The 3 cubic metre box is the largest of the

[12] Note that previously the terms “chemically toxic’ or ‘chemotoxic’ species have been used in place of non-radiological pollutants.

U-ILW containers for which RWM has provided waste package specifications [45] but it is recognised that this package is not sufficiently large to accommodate the full range of larger PCM waste items. The option of developing a LWC and associated large waste transport container (LWTC) is being explored and the development of a LWC design implementation plan, describing the scope of work, costs and timescales to progress the LWC concept to a level of maturity suitable for implementation has commenced. The implementation plan, when enacted, is expected to provide sufficient technical underpinning and substantiation of the LWC as a design solution and provide technical input to the relevant safety case(s) and LoC disposability assessments [46]. Furthermore, an Integrated Test, Evaluation and Acceptance Plan (ITEAP) template and guidance document has been produced which outlines how each of the LWC requirements will be verified and assessed [47].

In order to enable the production of the implementation plan and associated costing, a simple container design concept has been developed for the LWC based on an unshielded container similar to the 3 cubic metre box container but with an external (displacement) volume of approximately 9 m^3. The LWC / LWTC concept design is effectively the largest Type B package which could be transported by rail.

It is recognised that the LWC / LWTC concept is not large enough to accommodate all of the existing legacy, larger, PCM waste items, without further size reduction. The use of an even larger container could therefore minimise the need for size reduction of some waste items. Current Type IP-2 containers offer larger internal dimensions over the LWC / LWTC concept, but Type IP-2 containers are limited to the transport of LSA and SCO material, neither of which are likely to be applicable to larger PCM waste items.

Table 3 provides a summary of the key features of a range of waste containers larger than the 3 cubic metre box, which could potentially accommodate larger PCM waste items [48].

Table 3: Examples of waste containers that could potentially accommodate larger PCM waste items

Container	Internal Cavity Dimensions (mm)			Shielding Thickness (mm)	Gross Mass (te)	Internal Disposal Volume (m^3)	Transport Package Type Required
	Length	Width	Height				
LWC [49]	2960	1610	2010	NA	30	~5	Type B (Conceptual LWTC)
4m SAFSTORE [50] – 75 mm shielding	3485	2270	1900	Up to 120	32	17	Type IP-2 container (in its own right)
Croft 4m ILW box with 200 mm shielding [51]	3484	1639	1909	Up to 300	47.5 (100 mm shielding) 42.5 (200 mm shielding) 35.5 (300 mm shielding)	13.5 (100 mm shielding) 10.9(200 mm shielding) 8.1 (300 mm shielding)	Type IP-2 container (in its own right)
6 cubic metre Box [52]	~1958	~1730	~1720	~240 (concrete)	50	~5.8	Type IP-2 container (in its own right)

4.2. Balance of risks and opportunities

It is recognised that there are specific challenges associated with the management of larger PCM waste items relating to their physical size which may impact on a waste packager's ability to effectively characterise the activity and fissile content. To address uncertainties, an appropriate level of characterisation to effectively sentence the waste could vary from examination of records, relatively simple characterisation such as utilising endoscopes to significant intrusive/disruptive activities. The level of effort would be determined by following BAT/BPM, applying a proportionate approach (as discussed in Section 1.2) to managing waste in a safe and legal manner, whilst also seeking to balance the risks across the lifecycle of the waste stream. Engagement with RWM and the Regulators is encouraged when identifying a suitable characterisation regime to ensure the subsequent waste management process is optimised based on the most practicable characterisation data.

Having undertaken sufficient characterisation, the waste packager will be able to determine the extent to which further work is required. Further work could involve, for example, the minimisation of voidage or the immobilisation of radionuclides and particulates to satisfy transport and disposal requirements. The required level of effort increases with increasing waste item challenges. In general, there is likely to be a point reached where the effort required to resolve a challenge is not proportionate to the benefit gained. It is recognised that for certain aspects, for example, meeting a criticality safety case, then the level of effort required will be as much as is needed to meet those requirements. However, for other aspects such as voidage, there may be a balance where further effort doesn't result in a noticeable benefit in waste package or disposal system performance.

This guidance introduces the concept of trade-offs from the perspective of managing on-site risks and costs to the waste packager, but also from the perspective of achieving increasing levels of confidence in the transport and disposability of a larger PCM waste item as the knowledge of the waste increases.

It needs to be recognised that during the assessment of trade-offs, wider aspects need to be considered than those directly associated with the management of the larger PCM waste item and would likely be addressed in the supporting BAT/BPM and ALARP assessments. These aspects include, but are not limited to:

- **availability of skills** – the availability of skilled personnel will need to be considered when determining how to manage a larger PCM waste item. For example, engineers with relevant experience and knowledge of larger PCM waste items may be available now but the longer the period between identifying a larger PCM waste item and determining a waste management route, the knowledge and skills may not be available.
- **foreclosure of future options** – in identifying a preferred waste management option, the trade-off between producing a package suitable for disposal on a short timescale which forecloses future options and managing an item so that future treatment options can be applied will need to be considered.
- **economic** – financial implications are likely to be a key consideration in any development of a waste management option for a larger PCM waste item and a trade-off between financial implications upfront to the waste packager should be considered against the potential implications for future generations.

The sub-sections below discuss key areas where trade-offs in each of the lifecycle stages may be relevant in developing an appropriate strategy for managing larger PCM waste items.

Characterisation

A progressive approach to characterisation may offer significant benefits to waste producers, with existing provenance, non-intrusive, intrusive and disruptive characterisation being utilised in succession, with work stopping whenever there is sufficient confidence to support disposition of the waste item or where it is demonstrated that further characterisation activities will not generate additional benefits.

It may be beneficial to consider that characterisation options would most likely only be undertaken if there is a realistic prospect of significantly improving characterisation data to the point where appreciable, additional benefits can be realised. The value of doing the characterisation work will need to be linked with existing understanding of the provenance of the waste item. For example, the data may provide confidence that certain characterisation activities could improve decisions by improving relevant data sets. Similarly, if existing data suggests characterisation work is unlikely to change the end point of the waste life cycle or significantly enhance confidence in key risk elements associated with it, this will help identify whether it is worth the risk and cost of undertaking the work. It is recognised that there will always be a need for sufficient characterisation to enable adequate management to satisfy the criticality safety case for each stage of the waste management lifecycle.

Pre-treatment and treatment

A number of potential techniques can be applied during the pre-treatment and treatment stages of the PCM waste item management lifecycle to facilitate the disposal of the item. These treatment techniques could be applied to achieve a number of results including the minimisation of voids, the fixing or removal of contamination or a degree of size reduction. Trade-offs could be realised between the extent to which some of these activities are undertaken and the results achieved, as discussed for voidage in Section 4.1.

If required, trade-offs may also be relevant when determining to what degree contamination of a larger PCM waste item is removed or fixed, or to what extent lower activity components or sections of an item are removed. It may be that certain sections of an item would, if segregated from the item, be suitable for an alternative disposal route. Whereas this may represent good application of the waste management hierarchy, it may not be considered BAT/BPM or ALARP to undertake segregation of the section if the effort expended does not result in comparable benefits.

Selection of containers

Containers compliant with disposal requirements can produce a significant cost burden for the waste packagers compared to the on-site storage containers currently used by a number of SLCs, which do not meet these current requirements. There may be an advantage to waste packagers in delaying placement of a larger PCM waste item into a container suitable for disposal at a GDF, such that a final container can be selected when other issues such as void space and final conditioning requirements are better understood. However, the containerisation of unconditioned waste would require a suitable interim storage facility and where such a facility is not available, a requirement will exist for prompt containerisation and conditioning.

For low fissile content waste items, a potential opportunity exists to utilise Type IP-2 containers. This approach has been used at Harwell for low fissile content PCM waste transfers. Current Type IP-2 containers include the 2 metre and 4 metre box. It was recognised that since both container designs are based around the design of a standard iso-freight container, the potential exists to utilise a 6m variant offering increased storage volume for lower activity PCM waste items, recognising that payload restrictions for grouted containers may then become prohibitive.

There is a concern that it may not be possible to package PCM waste in Type IP-2 containers as it may not be possible to demonstrate that the waste meets the SCO or LSA requirements for transport as defined by the IAEA. Clarification of this issue would potentially enable an increase in the amount of waste that could be packaged into Type IP-2 containers and may result in savings across the waste lifecycle.

Conditioning

Waste conditioning could involve entombing or encapsulating the waste item and assist in meeting a number of disposal requirements, including minimising radionuclide mobility. Although the intimate encapsulation of waste is generally seen as best practice, the *Disposal System Specification Part B – Technical Specification* does not explicitly require such an approach to the conditioning of waste and it is recognised that waste packages containing certain wastes may meet most, or all of the requirements of the *Disposal System Specification Part B – Technical Specification* as a consequence of the physical or chemical form of the waste and/or the radionuclide inventory.

Indeed for some waste types there are a number of drivers for not adopting a conditioning approach involving intimate encapsulation and the production of a non-encapsulated wasteform, including:

- reducing the overall conditioned waste volume by increasing the waste loadings of waste containers;
- reducing the worker dose during conditioning;
- reducing the costs of conditioning by the removal of the encapsulation process and the cost of conditioning materials etc.; and
- eliminating undesirable interactions between the waste and conditioning materials (e.g. the corrosion of metals in cement) and the reduction of wasteform expansion, the production of particulate corrosion products and gases such as hydrogen.

Clearly the waste types for which non-encapsulation offers a viable approach are limited, but for those which could be conditioned in this way, the cost and safety benefits could be significant. An example of a waste item which may be considered for non-encapsulation is an activated stainless steel item where the activity is inherently immobilised in the waste itself and the material is relatively inert.

If further waste conditioning is necessary, the timing of waste conditioning requires consideration. The timing when larger PCM wastes will be placed within a GDF has yet to be established and there may be a requirement for periods of interim storage on SLC sites, potentially for durations exceeding 40 years. This situation presents opportunities and challenges with respect to waste management. Significant technological advances may be made over such a time period which may provide a range of additional options with respect to how the waste is managed; an example could include developments in thermal treatment capability arising from the current research. In addition, over such a timeframe, the GDF siting process and concept designs will mature, providing greater clarity with respect to disposal requirements. The timeframe may present further opportunities for new approaches which cannot be applied at present.

Two case studies have been provided to demonstrate the approaches which could be applied to the lifecycle management of larger PCM waste items, including the options which could be considered at each stage. The first case study focuses on the management approaches that could be adopted for gloveboxes, whilst the second case study focuses on the management approaches for pipes.

5. Case Studies

Gloveboxes and pipes were identified in Table 2 as being representative of larger PCM waste items, being wide spread across the UK nuclear estate. The glovebox case study is intended to represent a historic waste arising, while the pipe case study represents a future arising. It is noted that to date, limited operating experience exists for managing larger PCM waste items, as most wastes have followed the PCM waste management baseline approach.

These case studies are presented as illustrative examples of how the approach and options presented within this guidance could be applied to a larger PCM item. They present a range of lifecycle management options, recognising that there is unlikely to be a single management route. The exact route taken to effectively manage the waste items will depend on a number of factors and there will be key decision points at various stages that would dictate the exact route. The potential benefits and limitations associated with each option are also presented. As a result, the studies below do not represent a “model answer” and waste packagers will need to engage with RWM via the Disposability Assessment process regarding management options for specific items to ensure that the resulting product is disposable in the GDF (Section 1.4).

5.1. Legacy glovebox

5.1.1. Description

This case study assumes that the glovebox (complete with windows) is an historical arising and is located within a storage facility on the site it originated. The glovebox is therefore likely to be wrapped (in a non-soluble wrap), or packaged within some form of containment. The glovebox has been through post-operational clean out but may still require decontamination, for example due to residual acids, loose powders and oils that may be present.

The material composition of the glovebox is predominantly stainless steel, with a small proportion of plastic, rubber and glass components.

5.1.2. Background

The glovebox is largely dry, although residual acids or oils on the inner surfaces of the glovebox cannot be ruled out. The glovebox will require further monitoring and assessment owing to some internal surfaces of the glovebox potentially being contaminated with residual activity. Additional steps may therefore be required during the characterisation and pre-treatment stage to identify the presence of any residual contaminants and hazardous material. These may need to be removed from the glovebox prior to packaging and treatment.

The internal volume of the glovebox represents voidage, which accounts for a large proportion of the total glovebox volume.

The main issues associated with the management and packaging of whole gloveboxes includes the following:

- the presence, level and nature of activity is uncertain, which may necessitate further characterisation;
- additional contaminants may be present;
- mixture of materials;
- free liquids;
- voidage; and

- the largest sections of the glovebox could be up to 3 m in length.

5.1.3. Possible solutions

It is unlikely that there will be a single management route for larger PCM waste items such as whole gloveboxes. For example, there are a number of uncertainties with respect to the current storage arrangements, with the level of containment (e.g. presence of wrappings) being variable. Additional contaminants and hazardous materials may also be present and would need to be addressed as part of the onward management process. Similarly, in some cases surface contamination may have been fixed using strippable coatings, while other gloveboxes may not have such coatings, rendering surface contamination mobile. The decision on whether to defer the conditioning of waste is another aspect that will direct the chosen management route.

Figure 2 and Figure 3 illustrate the possible management routes for whole gloveboxes. Figure 2 shows the potential steps and decision points leading up to containerisation and covers characterisation and pre-treatment requirements. Figure 3 shows the steps and decision points leading up to disposal, relating to interim storage and waste conditioning. Both figures identify the key decision points that will influence the specific route taken. The decision points identified in Figure 2 and Figure 3 will act as drivers that direct the selected management route. These drivers include the following:

- **The quality of the available characterisation data:** further data may be required if historical records are incomplete, or records are insufficient to show compliance with safety cases and inform on the most appropriate management route. However, the level of characterisation required will be dictated by the provenance and the storage conditions, with intrusive or even disruptive characterisation potentially being necessary for a glovebox that is heavily wrapped.
- **The presence of contaminants and hazardous materials:** the removal of residual acid, oils, powders and lead shielding may be necessary. In an untreated form, oils, acids and powders may not generate a compliant waste package. Segregation and potentially passivation of potentially hazardous materials may be required as part of the pre-treatment step.
- **The viability and benefits of decontamination:** sections of the glovebox may be amenable to decontamination to reduce the level of surface activity, residual acids and oils. However, there must be a clear benefit associated with decontamination; for example, where doing so would reduce the surface contamination significantly such that waste could be reclassified and consigned via alternative routes. Alternatively, decontamination would need to reduce activity levels to a point that would enable consideration of certain packaging options.
- **The size of the selected waste container:** the size of the waste container will dictate the extent of size reduction necessary to successfully package the glovebox. The use of a LWC (LWC concept design cavity dimensions 2.96 x 1.61 x 2.01 m) will result in fewer size reduction activities compared to the baseline PCM strategy, which is to package within a 200 litre drum followed by supercompaction.
- **The level and nature of the activity:** gloveboxes or sections of gloveboxes with high and mobile activity may require more extensive conditioning compared to glovebox sections with lower, or fixed activity. It may therefore be possible to segregate sections of the glovebox that have higher activity and condition the segregated sections separately to optimise packaging and conditioning.
- **Staged containerisation and conditioning:** there may be benefits in containerising the waste and interim storing, pending future conditioning. For example, if there are uncertainties surrounding the acceptability of a conditioned

waste package for disposal and the existing storage arrangements for the gloveboxes are acceptable, there may be benefits in delaying the treatment/conditioning process until there is more confidence in the routes being considered.

- **Ability of the waste packaging site to handle containers**: The site packaging the waste may have physical restraints such that it cannot accommodate certain waste containers.

Figure 2: Possible characterisation, pre-treatment and containerisation routes for whole gloveboxes

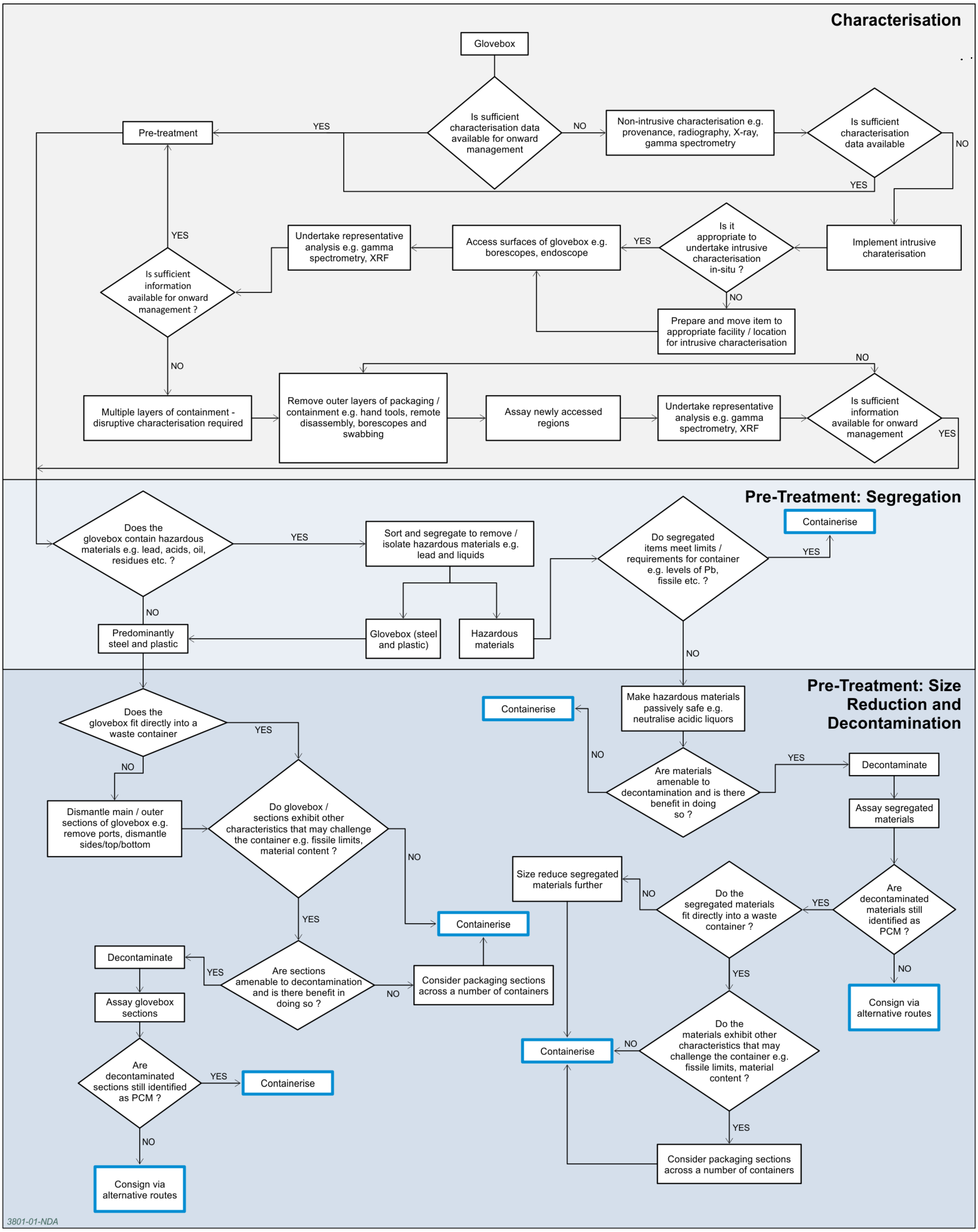
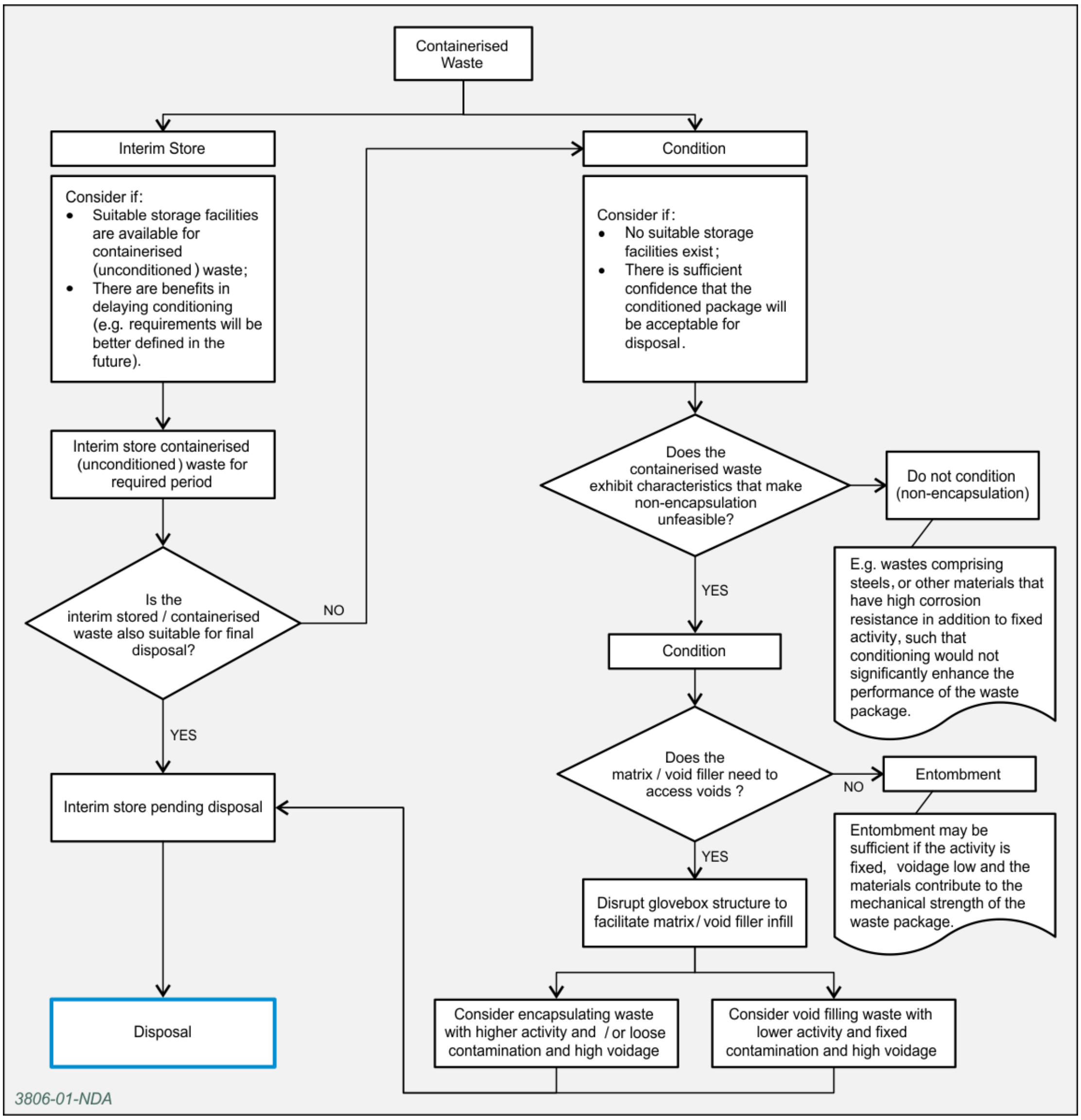


Figure 3: Possible interim storage and treatment routes for whole gloveboxes



5.1.4. Implementation

Table 4 summarises the high-level requirements and drivers for implementing some potential management routes presented in Figure 2 and Figure 3. As stated previously, it is unlikely that a single management route would be appropriate, with the route selected being dependent on whether the uncertainties identified above are realised. Therefore, not all of the requirements listed in Table 4 apply in all cases. It is likely that a toolbox of approaches (and hence requirements) would be necessary to successfully manage the treatment and packaging of a glovebox.

The identified drivers focus not only on direct financial considerations, but also from the perspective of the environment, health and safety, hazard reduction, socio-economic concerns and security. Where appropriate the drivers have been compared to the baseline PCM strategy (size reduction, package within a 200 litre drum followed by supercompaction, with pucks grouted into a 500 litre drum).

Table 4: Summary of requirements for the implementation of the different management routes for whole gloveboxes

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[13]
Characterisation: non-intrusive	If existing records are not sufficient to support the onward management of the glovebox then non-intrusive characterisation would be required.	• Historic records to understand provenance; • A toolbox of in-situ characterisation techniques e.g. radiography, X-ray, γ-spectrometry, XRF.	• No loss of containment so minimal exposure to the workforce; • Minimal risk to the workforce; • Greater risk of needing to re-work the package at a later date to enable disposal[14]; • Higher throughput rates; • Lower capital cost compared to the baseline, but larger long-term financial risk if the package needs to be re-worked at a later date to ensure compliance.
Characterisation: intrusive and disruptive	Required if non-intrusive characterisation is inconclusive e.g. if the glovebox is stored in multiple layers of wrapping.	• In-situ characterisation techniques for the more accessible surfaces; • Facility for the remote disruption of the glovebox, recognising that primary containment will be broken; • Ability to remotely observe and swab difficult to access areas of glovebox (e.g. endoscope and borescopes); • Provisions to analyse swabs in a laboratory to provide more representative assay data.	• Loss of containment would increase operator exposure; • Opportunity to identify and segregate lower level items and problematic items; • Potential release of contamination/ discharges from processing; • Secondary waste generated through sampling; • May require investment in new/ additional technologies.

[13] Drivers are not limited to cost, but may also include environment, health and safety, hazard reduction, socio-economic concerns and security.
[14] Non-intrusive characterisation may not provide representative data (due to some regions of the waste being inaccessible). If the full characteristics of the item are not known, there may be greater risk of needing to re-work the waste package at a later date to ensure compliance with disposal requirements.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[13]
Pre-treatment: sort and segregation	Required if hazardous materials are present e.g. residual powders and liquids.	• Facility for the remote segregation of waste, recognising that primary containment will be broken; • Provisions for handling potentially pyrophoric materials (e.g. finely divided metal) from inside the glovebox; • Ability to handle and treat oils and acids.	• Loss of containment would increase operator exposure; • Opportunity to identify and segregate lower level items and problematic items; • Potential release of contamination/ discharges from processing; • Costs are likely to be equivalent to the baseline.
Pre-treatment: size reduction	Required if the whole glovebox or sections of the glovebox do not fit directly within the waste container (e.g. LWC) without size reduction.	• Provisions for undertaking size reduction activities, which may include both manual and remote size reduction activities; • Ability to handle and dispose of secondary waste generated through cutting operations.	• Lower number of size reduction activities required compared to the baseline owing to larger container; • Reduced number of operations and manual interventions compared to the baseline; • Reduced operator exposure; • Increased speed/ time saving compared to baseline; • Opportunity for waste segregation.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[13]
Pre-treatment: decontamination	This stage is only necessary if any of the segregated glovebox components are amenable to decontamination and there are clear benefits of undertaking decontamination activities.	• Provisions for undertaking decontamination operations using chemical or mechanical means; • Ability to assay the decontaminated items after treatment to determine the most appropriate disposal route e.g. remain within PCM stream, or consign to alternative routes; • Ability to manage secondary waste arisings from the decontamination step.	• Increased operator exposure; • Increased manual interventions; • Generation of secondary waste; • Potential release of contamination/ discharges from processing; • Opportunity to reclassify waste and consign through alternative routes; • Opportunity to utilise alternative containers e.g. Type IP-2; • Additional processing step, increasing overall costs, but may reduce the overall volume of waste consigned as PCM requiring GDF disposal.
Containerisation	The use of the LWC is a novel concept, so there are additional considerations surrounding its implementation.	• Facility and associated infrastructure for handling and loading the LWC; • Appropriate transport routes within the site to allow the transportation of the LWC during the interim storage period leading up to disposal; • Infrastructure at a GDF for handling and operating the LWC.	• LWC are more expensive than the baseline 200 litre drum; • However, fewer LWC would be required; • Longer-term financial risk associated with the uncertainties surrounding implementation of the LWC.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[13]
Treatment: non-encapsulation	Non-encapsulation may be suitable for waste items displaying certain characteristics, which may include: fixed activity, high corrosion resistance, absence of hazardous substances and good mechanical strength.	• Facility for packing waste within the chosen container; • The use of internal furniture may be required to support the unconditioned waste within the package.	• More consideration to the use of internal furniture compared to baseline; • Higher throughput; • Reduced secondary waste; • Reduced discharges; • No additional materials required; • Reduced cost compared to the baseline.
Treatment: entombment	Entombment is the introduction of a conditioning matrix (e.g. cementitious grout) that surrounds the waste item. Entombment may be considered for waste items that do not require void spaces to be filled and may be applicable to waste packages that display a minimal amount of voidage.	• Plant capable of supplying the matrix on the scales required.	• The level of processing required is still lower than the baseline, so overall lower operator risk and exposure; • Relatively simple processing; • Costs likely to be lower than baseline.
Treatment: encapsulation	Encapsulation or flood grouting involves combining a conditioning matrix (e.g. cementitious grout) with the waste material. Encapsulation of the glovebox may be the most appropriate route if activity is high and mobile.	• Encapsulation plant capable of supplying the conditioning matrix on the scales required for the glovebox; • Ability to disrupt the glovebox and/ or glovebox sections so the conditioning matrix can infiltrate through the waste materials.	• Increased processing requirement due to the glovebox being disrupted, representing an additional step compared to the baseline; • Increased interventions, so increased operator risk and exposure.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[13]
Treatment: void filling	Void filling is the introduction of an inert material (e.g. sand, crushed limestone, fly ash or glass beads) to the waste package. The role of the inert material is to fill the void space created by the presence of the waste materials within the package. Further information relating to void filling materials can be found in Reference [7]. Void filling may be more appropriate for lower activity items, or waste packages displaying high levels of voidage.	• Plant capable of supplying the void filling material on the scales required; • Ability to disrupt the glovebox and/ or glovebox sections so the void filling material can infiltrate and fill the voids spaces.	• Increased processing requirement due to the glovebox being disrupted representing an additional step compared to the baseline; • Increased interventions, so increased operator risk and exposure.
Interim storage: deferred conditioning	Where there are benefits associated with delaying conditioning, the waste may be interim stored (unconditioned).	• Storage facility capable of storing unconditioned waste; • Adequate controls and arrangements for managing the containerised (unconditioned) waste; • Adequate records relating to each package being interim stored to facilitate future conditioning activities.	• Higher throughput; • Reduced secondary waste; • Reduced discharges; • No additional materials required; • Improved short-term affordability compared to the baseline; • The interim storage costs associated with deferred conditioning may increase the long-term costs compared to the baseline; • Low risk, as waste can be re-worked if required.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[13]
Interim storage: pending disposal	Following containerisation and conditioning, the final waste packages will be stored prior to disposal.	• Storage facilities capable of storing final waste packages; • Adequate controls and arrangements for managing final waste packages; • Adequate records relating to each waste package destined for disposal.	• Similar to baseline where interim storage of grouted/ conditioned packages is undertaken prior to disposal; • However, fewer packages containing large PCM items expected compared to baseline, so overall reduced cost of interim storage due to reduced numbers of packages requiring inspection and monitoring.

5.1.5. Potential benefits and limitations

The selected waste management route needs to be safe during all phases of the waste management lifecycle. However, as noted in Section 1, there needs to be a balance between near term risks to the operator health and safety, longer term risks to transport and disposability, alongside financial constraints. Hence, the principles of BAT/BPM and ALARP shall be taken into consideration. As previously discussed, as the challenges associated with the waste item increase, so does the level of work required to resolve these challenges. The sections below summarise the potential benefits and limitations for each lifecycle stage in relation to gloveboxes.

Characterisation

Characterisation of the glovebox will be required at various stages of the lifecycle, with initial characterisation being required to inform on the most appropriate management route and to realise any opportunities to reclassify waste from ILW to LLW. There may be benefits in adopting a progressive characterisation approach with existing provenance, non-intrusive, intrusive and disruptive characterisation being utilised in succession, with work stopping whenever there is sufficient confidence to support disposition of the glovebox or where it is demonstrated that further characterisation activities will not generate additional benefits.

Following the initial characterisation, further characterisation is likely to be required in support of the pre-treatment process (e.g. following any decontamination steps) to gain a better understanding of the glovebox inventory.

The benefits and limitations of the various types of characterisation approach likely to be adopted are outlined in Table 5.

Table 5: Benefits and limitations of characterisation approaches

Benefits	Limitations
Non-Intrusive	
No release of activity.	Hazardous materials, or regions of higher activity (e.g. within corners of the glovebox) may not be identified.
Higher throughput.	Limited opportunity to segregate hazardous materials.
Low cost	Limited opportunity to segregate lower activity glovebox sections from higher activity sections.
Low dose	Risk that package will not be acceptable for disposal.
	May rely on historic records being available and sufficiently detailed to inform on the preferred onward route.
Intrusive and Disruptive	
Identification of hazardous materials, or regions of the glovebox that are highly	Breaking containment (e.g. removing wrapping, or accessing internal surfaces)

contaminated.	could disperse activity.
Potential to reclassify waste.	Inconclusive results could necessitate further disruption, increasing activity dispersal and discharges.
Increased likelihood of the waste package being acceptable for disposal.	May have to undertake several intrusive characterisation steps to ensure that representative results are obtained i.e. cannot assume that the entire glovebox is contaminated to the same level (e.g. contamination build-up may be higher inside the glovebox within corners).
	Generation of secondary waste.

Pre-treatment

The pre-treatment steps that may apply to gloveboxes are shown in Figure 2, potentially including segregation, size reduction and decontamination. The benefits and limitations of these processes are summarised in Table 6.

Table 6: Benefits and limitations of pre-treatment approaches

Benefits	Limitations
Segregation	
Passivation of powders, oils and acidic residues.	Increased operator exposure and risk.
Segregation of lead and other materials that could potentially be diverted through alternative routes (e.g. recycling, disposal to LLWR, or decontamination followed by LLWR disposal)	Additional management routes would be required to passivate hazardous materials e.g. neutralise acids, immobilise powders, decontaminate and dispose oil.
Segregating hazardous materials minimises the probability of the waste package being unacceptable for disposal.	Increased number of manual interventions.
Segregation could result in glovebox sections being reclassified, diverting materials away from the PCM stream and reducing the volume of waste requiring packaging and conditioning.	High cost of facilities needed to enable size reduction.
Size Reduction	
Dismantling the main glovebox frame would minimise voidage within the waste package.	Increased operator exposure and risk.
More efficient packaging achievable through size reduction (e.g. cutting, shredding), potentially opening up alternative	Increased number of manual interventions.

Benefits	Limitations
conditioning routes e.g. non-encapsulation or entombment instead of encapsulation and void filling.	
The number of cuts required would be lower than the baseline PCM strategy owing to the larger size of the waste container.	
Decontamination	
Decontamination could result in glovebox sections being reclassified, diverting materials away from the PCM stream and reducing the volume of waste requiring packaging and conditioning.	Generates secondary waste and discharges.
Decontamination (or the use of hold-down/ tie-down coatings) could open up certain conditioning routes e.g. non-encapsulation and entombment instead of encapsulation and void filling.	Increased operator exposure and risk.
	Increased number of manual interventions.

Containerisation

Figure 3 shows that waste from the glovebox could be containerised and interim stored in an unconditioned form until a decision is made on the most appropriate conditioning route. Alternatively, the waste could be conditioned immediately following containerisation and the final waste package interim stored pending GDF disposal. The benefits and limitations relating to the containerisation of gloveboxes using LWCs or 3 cubic metre boxes, compared to the baseline PCM strategy are outlined in Table 7.

Table 7: Benefits and limitations of containerisation

Benefits	Limitations
The increased size of the container would result in fewer containers requiring interim storage.	If conditioning is deferred, a storage facility suitable for storing containerised (unconditioned) waste would be required.
Fewer containers would result in a reduced inspection and monitoring burden on the site during interim storage.	Larger containers may require a greater site infrastructure for effective handling.
A staged approach to containerisation means that the NDA's mission can be progressed - the management of gloveboxes could progress with the containerisation of waste being undertaken even if the final treatment/ conditioning route has not been finalised.	

Benefits	Limitations
Deferring containerisation for GDF disposal could minimise the risk of waste packaged being produced that are later found to be unacceptable. This approach could also prevent waste packages being over engineered.	

Treatment and conditioning

The conditioning approaches identified for gloveboxes (Figure 3) include non-encapsulation, entombment, encapsulation and void filling. The benefits and limitations of each treatment and conditioning approach are summarised in Table 8.

Table 8: Benefits and limitations of treatment and conditioning

Benefits	Limitations
Non-Encapsulation	
A more cost effective option.	Potentially only suitable for a small number of packages e.g. packages containing waste with high corrosion resistance, good mechanical strength, low voidage and fixed activity.
High throughput route.	
Reduced operator exposure and intervention.	
Entombment[15]	
Relatively high throughput.	Potentially only suitable for a small number of packages, such as those exhibiting low voidage (e.g. for dismantled sections of gloveboxes that are stacked within the container, thus removing voidage through increased packaging efficiency).
Encapsulation[16]	
Ensures that any mobile activity (e.g. residual powders) on the glovebox surfaces are immobilised.	May require gloveboxes, or glovebox sections to be disrupted for matrix in-fill.

[15] Entombment is the introduction of a conditioning matrix (e.g. cementitious grout) that completely surrounds the waste.
[16] Encapsulation or flood grouting is the combination of a conditioning matrix (e.g. cementitious grout) with the waste material. This does not need to involve active mixing.

Benefits	Limitations
In-fill of all voidage would be required for gloveboxes that are packaged whole, or those that are only partially disassembled and have significant voidage.	Greater development work may be required to ensure that encapsulation has been successful and that the waste packages generated display the required characteristics e.g. low voidage.
Increased likelihood of waste packages being acceptable for future disposal.	Greater processing requirements and operator involvement.
Void Filling[17]	
In-fill of all voidage, which would be required for gloveboxes that are packaged whole, or those that are only partially disassembled and have significant voidage.	May require gloveboxes, or glovebox sections to be disrupted for the void filler to infiltrate into the void spaces.
Increased likelihood of waste packages being acceptable for future disposal.	Greater development work may be required to ensure that the void filling material has successfully infiltrated the waste and that the package displays the required characteristics e.g. low voidage.
	Void filling may reduce voidage and increase mechanical strength of the package, but it may not adequately fix mobile activity associated with gloveboxes, or perform other functions that would render the waste package passively safe.
	Greater processing requirements and operator involvement.

5.2. Future pipework arising

5.2.1. Description

This case study relates to pipework that is currently in-situ and connected to equipment, which may include gloveboxes, vessels or ventilation systems within a facility. Pipework is found across the NDA estate, such that it can be considered as being as representative large item (Table 2). The pipework considered in the following case study is assumed to consist of 100% steel of unspecified grade.

5.2.2. Background

Pipework may remain connected to equipment which may not be easily accessible. Additional containment (e.g. covers and lagging) may surround the pipework which will need to be removed to access the pipes for processing.

The pipework is assumed to be largely dry, although internal areas may be contaminated with dried residual liquors (e.g. acidic solutions) if connected to tanks and vessels, or liquor

[17] Void filling is the introduction of an inert material to the waste package. The role of the inert material is to fill the void space created by the presence of the waste materials within the package.

from regions of the pipework where hold-up may occur e.g. in U-bends, valves, or bulk heads. Alternatively, pipework from ventilation systems may contain particulate material. Additional steps may be required during the characterisation and pre-treatment stages to remove these materials from the pipework.

There is an expected voidage associated with the internal bore of the pipework. Pipework sections of various lengths are expected to arise from facilities. Long sections of pipe may not fit directly within existing waste containers, such that further processing may be required prior to containerisation (e.g. size reduction).

The main issues associated with the management and packaging of pipework includes the following:

- characterisation will be required if the operational records are incomplete, or uncertainties within the records exist that limit their use in informing the onward waste management;
- potential for the presence of free liquids within the pipe (not expected in this case);
- additional contaminants potentially present;
- variable voidage from the internal bore of the pipes; and
- large and variable size.

5.2.3. Possible solutions

It is unlikely that there will be a single management solution for contaminated pipework so this guidance is not fully encompassing. There will be a number of variables that will influence onward management. For example, the pipes are in-situ within a facility, such that they may not be accessible without the removal of external covers or lagging, which could impact on the characterisation and size reduction activities. Furthermore, the contamination within the pipework system may not be uniformly distributed, such that more intrusive or disruptive characterisation may be required to fully assess the inventory.

Figure 4 and Figure 5 illustrate the possible management routes for pipework. Figure 4 shows the potential steps and decision points leading up to containerisation including characterisation and pre-treatment. Figure 5 shows the steps and decision points leading up to disposal, which includes interim storage and waste conditioning. Both figures identify key decision points that will dictate the exact route taken. The decision points identified in Figure 4 and Figure 5 will act as drivers that direct the selected management route. These drivers include the following:

- **Provenance and availability of the operational records:** it is assumed that since the pipework is either an existing, or a future arising, sufficient operational records may be available to inform on the physical, chemical and radiological characteristics of the pipework. However, if records are not adequate (for example, some future arisings may reside in old facilities that have not been operated for some time and have relatively poor records), or there are uncertainties relating to the waste characteristics, additional characterisation would be required. The level of characterisation required would be dependent on the existing containment surrounding the pipework and the variability in contamination levels throughout the pipework system.
- **The presence of contaminants and hazardous materials:** pipework originating from vessels and gloveboxes may be contaminated with residual acidic liquors, whilst pipework from ventilation systems may contain particulate material. The decontamination of pipework to remove any contaminants may be necessary to ensure that the final waste package is acceptable for future disposal. Alternatively, decontamination may be implemented to reduce activity levels to a point that would

make certain packaging options open for consideration, or to reclassify waste from ILW to LLW. However, there must be a clear benefit associated with decontamination; for example, doing so would reduce the surface contamination significantly such that waste could be reclassified and consigned via alternative routes.

- **The size of the selected waste container:** Where direct loading into an RWM container is the preferred solution, the size of the waste container will dictate the extent of size reduction necessary to successfully package the pipework. The use of a LWC (LWC cavity dimensions 2.96 x 1.61 x 2.01 m) would result in fewer size reduction activities compared to the baseline PCM strategy.
- **The internal bore of the pipework:** the internal diameter, or bore, of the pipework represents the most significant voidage. Therefore, large bore pipes could be compacted to flatten the lengths of pipework and remove the internal voidage. Alternatively, the pipes could be cut along their longitudinal length to create half-pipes, which could then be stacked within the waste container to eliminate the voidage created by whole, un-disrupted pipework.
- **Staged containerisation and conditioning:** there may be benefits in containerising the waste and interim storing it pending future conditioning. For example, if there are uncertainties surrounding the acceptability of a conditioned waste package for disposal, or if the existing storage arrangements for the pipes are not posing any issues, then there may be benefits in delaying the treatment/ conditioning process until there is more confidence in the routes being considered.
- **Treatment and conditioning:** a number of treatment and conditioning routes are available, with the most appropriate route being dictated by the nature of the pipework and the pre-treatment implemented prior to containerisation. For example, pipework exhibiting low voidage (due to compaction, or cutting) may be suitable for non-encapsulation or entombment. Conversely, encapsulation and void filling may be more suitable for pipework displaying significant voidage, higher levels of activity or mobile activity.

Figure 4: Possible characterisation and pre-treatment routes for pipework

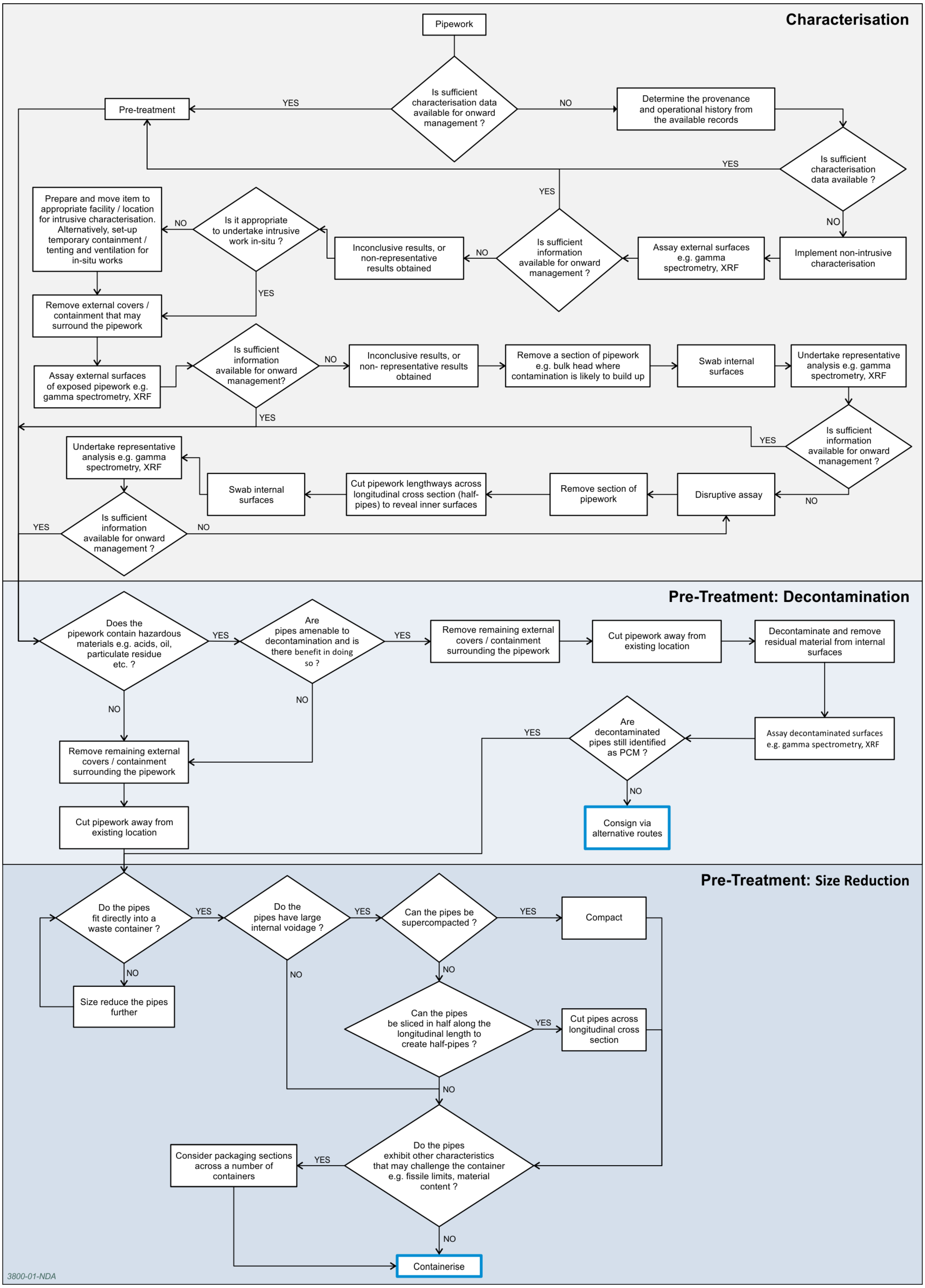
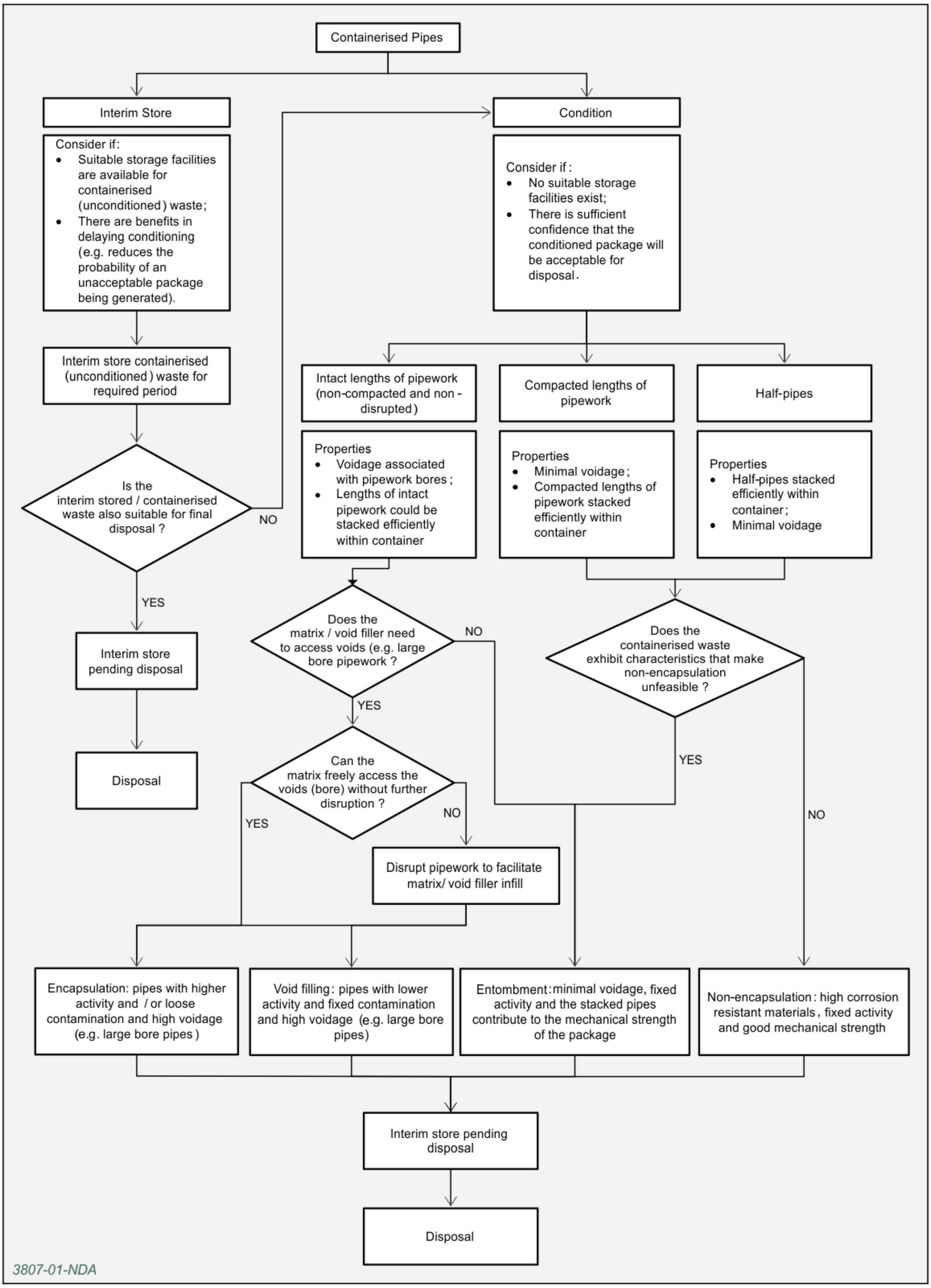


Figure 5: Treatment and containerisation routes for pipework



5.2.4. Implementation

Table 9 summarises some high-level requirements and drivers for consideration for waste producers implementing the various management routes presented in Figure 4 and Figure 5. As stated previously, it is unlikely that a single management route would be appropriate, with the route selected being dependent on whether the uncertainties identified above are realised. Therefore, not all of the requirements listed in Table 9 would be necessary. It is more likely that a toolbox of approaches (and hence requirements) would be necessary to successfully manage the treatment and packaging of pipework sections.

The identified drivers focus not only on financial considerations, but also from the perspective of the environment, health and safety, hazard reduction, socio-economic concerns and security. Where appropriate, the cost drivers have been compared to the baseline PCM strategy.

Table 9: Summary of requirements for the implementation of the different management routes

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[18]
Characterisation: non-intrusive	If existing operational records are not sufficient to support the onward management of the pipework, or there are uncertainties surrounding the records, then non-intrusive characterisation would be required.	• Historic records to understand provenance; • A toolbox of in-situ characterisation techniques e.g. radiography, X-ray, γ-spectrometry, XRF.	• No loss of containment so minimal exposure to the workforce; • Minimal risk to the workforce; • Greater risk of re-working the package at a later date; • Higher throughput rates; • Lower capital cost compared to the baseline, but larger long-term financial risk.
Characterisation: intrusive	Required if non-intrusive characterisation is inconclusive e.g. if the pipework is located behind external covers or lagging.	• In-situ characterisation techniques for the more accessible surfaces; • Removal of external covers/ lagging to expose external surfaces for characterisation; • Temporary tent and ventilation to allow the pipework to be removed, recognising that primary containment would have been broken; • Ability to swab the internal surfaces of the pipework following intrusion (e.g. endoscope and borescopes); • Provisions to analyse swabs in a laboratory to provide more representative assay data.	• Loss of containment would increase operator exposure; • Opportunity to identify and segregate lower level pipework; • Potential release of contamination/ discharges from processing; • Secondary waste generated through sampling; • May require investment in new/ additional technologies.

[18] Drivers are not limited to cost, but may also include environment, health and safety, hazard reduction, socio-economic concerns and security.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[18]
Characterisation: disruptive	Required if non-intrusive and intrusive characterisation approaches prove to be inconclusive e.g. if the contamination is not consistently distributed across the pipework system, such that representative sampling and analysis is required.	• Temporary tent and ventilation to allow larger sections of pipework to be completely removed from the existing location; • Tools for removing the pipework sections from the installation; • Tools for cutting the pipework along its longitudinal cross section to reveal the internally contaminated surfaces; • In-situ characterisation techniques to assay the internal surfaces exposed through cutting.	• Further loss of containment would increase operator exposure; • Opportunity to identify and segregate lower level pipework; • Release of contamination/ discharges from processing; • Secondary waste generated through sampling and cutting operations; • May require investment in new/ additional technologies e.g. cutting techniques to disrupt pipework; • Higher capital cost compared to the baseline, but lower long-term financial risk.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[18]
Pre-treatment: size reduction	Required if the pipework sections that have been removed from the facility do not fit directly within the waste container (e.g. LWC) without additional size reduction. Additional size reduction may also be required to facilitate efficient packaging within the waste container. For example, the pipes could be cut along their longitudinal cross section to create half-pipes, which could be stacked within the container to reduce voidage and increase packing efficiency.	• Provisions for undertaking size reduction activities, which may include both manual and remote size reduction activities and ventilation; • Cutting techniques allowing the pipes to be cut into half-pipes; • Ability to handle and dispose of secondary waste generated through cutting operations.	• Half the number of size reduction activities required compared to the baseline owing to larger container; • Reduced number of operations and manual interventions compared to the baseline; • Reduced operator exposure; • Increased speed/ time saving compared to baseline; • Opportunity for waste segregation.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[18]
Pre-treatment: decontamination	This stage is only necessary if any of the pipework sections are amenable to decontamination and there are clear benefits of undertaking decontamination activities.	• Provisions for undertaking decontamination operations using chemical or mechanical means; • Ability to assay the decontaminated items after treatment to determine the most appropriate disposal route e.g. remain within PCM stream, or consign through alternative routes; • Ability to manage secondary waste arisings from the decontamination step; • If effluent treatment facilities are available, then In-situ flushing of pipes to remove internal contamination.	• Increased operator exposure; • Increased manual interventions; • Generation of secondary waste; • Potential release of contamination/ discharges from processing; • Opportunity to reclassify waste and consign through alternative routes; • Additional processing step, increasing overall costs, but may reduce the overall volume of waste consigned as PCM requiring GDF disposal.
Pre-treatment: compaction	This stage is only necessary if the pipework sections are suitable for compaction once removed from the equipment/ facility.	• Access to an industrial compactor suitable for compacting lengths of pipework.	• Decreased operator exposure; • Decreased manual interventions (compared to cutting operations); • Reduced secondary waste (compared to cutting operations); • Reduced volume of waste requiring packing and conditioning; • Costs are likely to be equivalent to the baseline.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[18]
Containerisation	The use of the LWC is a novel concept, so there are additional considerations surrounding its implementation.	• Facility and associated infrastructure for handling and loading the LWC; • Appropriate transport routes within the site to allow the transportation of the LWC during the interim storage period leading up to disposal; • Infrastructure at the GDF for handling and operating the LWC.	• LWC are more expensive than the baseline 200 litre drum; • However, fewer LWC would be required; • Longer-term financial risk associated with the uncertainties surrounding implementation of the LWC.
Treatment: non-encapsulation	Non-encapsulation may be suitable for pipes displaying certain characteristics, which may include: fixed activity, high corrosion resistance, low voidage and good mechanical strength.	• Facility for packing waste within the chosen container; • The use of internal furniture may be required to support the unconditioned waste within the package.	• More consideration to the use of internal furniture compared to baseline; • Higher throughput; • Reduced secondary waste; • Reduced discharges; • No additional materials required; • Reduced cost compared to the baseline.
Treatment: entombment	Entombment is the introduction of a conditioning matrix (e.g. cementitious grout) that surrounds the waste item. Entombment may be considered for pipes that do not require void spaces to be filled and may be applicable to waste packages that display a minimal amount of voidage and fixed activity.	• Plant capable of supplying the matrix on the scales required.	• The level of processing is still lower than the baseline, so overall lower operator risk and exposure; • Relatively simple processing; • Costs likely to be lower than baseline.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[18]
Treatment: encapsulation	Encapsulation or flood grouting involves combining a conditioning matrix (e.g. cementitious grout) with the waste material. Encapsulation of the pipework may be the most appropriate route if activity is high and mobile and there is a significant amount of voidage.	• Encapsulation plant capable of supplying the conditioning matrix on the scales required for the containerised pipes; • Ability to disrupt the pipework (e.g. drilling through walls) so the conditioning matrix can infiltrate through the pipes and fill the internal voids.	• Increased processing due the pipework being disrupted, representing an additional step compared to the baseline; • Increased interventions, so increased operator risk and exposure.
Treatment: void filling	Void filling is the introduction of an inert material (e.g. sand, crushed limestone, fly ash or glass beads) to the waste package. The role of the inert material is to fill the void space created by the presence of the waste materials within the package. Further information relating to void filling materials can be found in Reference [7]. Void filling may be more appropriate for lower activity items, or waste packages displaying high levels of voidage (e.g. large bore pipes).	• Plant capable of supplying the void filling material on the scales required; • Ability to disrupt the pipework (e.g. drilling through walls) so the void filling material can infiltrate through the pipes and fill the internal voids.	• Increased processing due the pipework being disrupted representing an additional step compared to the baseline; • Increased interventions, so increased operator risk and exposure.

Stage of Life Cycle	Description and Requirement	What would be Required for Implementation?	Drivers[18]
Interim storage: deferred conditioning	Where there are benefits associated with delaying conditioning, the pipes may be interim stored (unconditioned).	• Storage facility capable of storing unconditioned waste; • Adequate controls and arrangements for managing the containerised (unconditioned waste); • Adequate records relating to each package being interim stored to facilitate future conditioning activities.	• Higher throughput; • Reduced secondary waste; • Reduced discharges; • No additional materials required; • Reduced cost compared to the baseline; • Low risk, as waste can be re-worked if required.
Interim storage: pending disposal	Following containerisation and conditioning, the final waste packages containing conditioned pipes will be stored prior to disposal.	• Storage facilities capable of storing final waste packages; • Adequate controls and arrangements for managing final waste packages; • Adequate records relating to each waste package destined for disposal.	• Similar to baseline where interim storage of grouted/ conditioned packages is undertaken prior to disposal; • However, fewer packages containing large PCM items expected compared to baseline, so overall reduced cost of interim storage due to reduced numbers of packages requiring inspection and monitoring.

5.2.5. Potential benefits and limitations

It was discussed previously in the glovebox case study that the waste management processes chosen for larger PCM waste items would need to be safe during all phases of the waste management lifecycle. However, the principles of BAT/BPM and ALARP would need to be taken into consideration to balance the near term risks to the operator health and safety, longer term risks to transport and disposability, alongside financial constraints. These considerations also apply to pipes that are retrieved from a facility and processed for disposal. The sections below summarise the potential benefits and limitations for each lifecycle stage in relation to pipes.

Characterisation

As with gloveboxes, it is likely that there will be a requirement to characterise pipes at various stages of the management lifecycle to inform the selection of the most appropriate management route and also to realise any opportunities to reclassify waste from ILW to LLW.

Initially characterisation may involve reviewing the operational history of the pipework and understanding its provenance. However, if records are incomplete, or there are uncertainties surrounding the records, then additional characterisation may be required. A progressive approach to characterisation, such as that described previously for gloveboxes, may be beneficial. Figure 4 shows that in terms of pipework (in-situ within a facility), this may firstly involve removing any external covers and lagging covering the pipework, followed by removing a small section of pipework (e.g. bulk head or valve to reveal a small section of the internal surfaces), before removing and disrupting larger sections of pipework. This progressive approach would allow work to stop when there is sufficient confidence to support the onward management, or where further characterisation is not thought to offer additional benefits.

Characterisation may also be required following decontamination activities to confirm the success of the decontamination step, and also to determine whether the decontaminated pipework could potentially be reclassified and consigned through alternative routes.

The benefits and limitations of the various types of characterisation approach likely to be adopted are outlined in Table 10.

Table 10: Benefits and limitations of characterisation approaches

Benefits	Limitations
Non-Intrusive	
No release of activity.	Hazardous materials, or regions of higher activity (e.g. within valves or bulk heads, where contamination build-up could potentially occur) may not be identified.
Higher throughput.	Limited opportunity to segregate lower activity pipe sections from higher activity sections.
Operational records that inform on the provenance and hence chemical and radiological characteristics are likely to be available due to the pipes and associated equipment being recently utilised.	Only suitable if operational records are sufficiently detailed to inform on the onward management.

Benefits	Limitations
	Risk that package will not be acceptable for disposal.
Intrusive	
Identification of hazardous materials or regions of highly contaminated pipework could be possible.	Breaking containment (e.g. removing pipes to access internal surfaces) could disperse activity.
Potential to reclassify pipework.	Inconclusive results could necessitate further disruption, increasing activity dispersal and discharges.
Access to the internal surfaces may improve the quality of the characterisation data, providing more confidence in the nature of the waste to support future disposal.	May have to undertake several intrusive characterisation steps to ensure that representative results are obtained as it cannot be assumed that the entire pipework system is contaminated to the same level (e.g. contamination build-up may be higher in pipe bends/ elbows and bulk-heads).
Crimping the pipes followed by cutting along the crimped sections could minimise the dispersal of activity.	Increased exposure risk to operators.
Disruptive	
Access to the internal surfaces may improve the quality of the characterisation data, e.g. allowing any highly contaminated areas to be identified. This could provide more confidence in the nature of the waste to support future disposal.	Greatest exposure risk to operators.
Disrupted pipework e.g. if cut along longitudinal cross section into half-pipes, may be packaged more efficiently during containerisation, reducing voidage and potentially avoiding the requirement for extensive conditioning.	Requires cutting/ disassembly tools for accessing internal pipework surfaces.
	Generation of secondary waste.

Pre-treatment

The pre-treatment steps of relevance to pipework are shown in Figure 4 and include size reduction, decontamination and compaction. The benefits and limitations of these processes are summarised in Table 11.

Sorting and segregation has not been recognised as a separate pre-treatment step for pipework since the pipes are assumed to be comprised of steel and not a mixture of material types (as may be the case for gloveboxes). However, it is acknowledged that some sort and segregation activities may take place following decontamination, where the decontaminated pipework sections are re-assayed to determine if they are still identified as PCM. Sorting and segregation would therefore take place in the sense that any decontaminated items that are not classed as PCM could be diverted away from the ILW/ PCM route and consigned through alternative routes.

Table 11: Benefits and limitations of pre-treatment approaches

Benefits	Limitations
Size Reduction	
Size reduction could minimise voidage in the container due to increased packing efficiency.	Increased operator exposure and risk.
Reduced voidage through size reduction could potentially make certain conditioning routes (e.g. non-encapsulation or entombment) more viable.	Increased number of manual interventions.
The number of cuts required would be lower than the baseline PCM strategy owing to the larger size of the waste container.	
Decontamination	
Decontamination could result in the pipework sections being reclassified, diverting materials away from the PCM stream (e.g. to alternative consignment routes, or to LLWR) and reducing the volume of waste requiring packaging and conditioning.	Generates secondary waste and discharges.
Decontamination could open up certain conditioning routes e.g. non-encapsulation and entombment instead of encapsulation and void filling.	Increased operator exposure and risk.
	Increased number of manual interventions.
Compaction	
Reduces internal voidage associated with pipes (particularly large bore pipes).	Some secondary waste generated.

Benefits	Limitations
Increased packing efficiency achievable if the compacted pipes are stacked within the waste container. This could minimise voidage and make certain conditioning routes viable.	Some operator exposure and risk.
Minimal cutting operations required. The pipes would need to be cut from their existing location. The only additional cutting would be to ensure the sections fit within the container.	
Compaction offers an alternative size reduction and void minimisation activity to traditional cutting, while minimising operator exposure/ manual operations.	

Containerisation

Figure 5 shows that waste could be containerised and interim stored in an unconditioned form until a decision is made on the most appropriate conditioning route. Alternatively, the waste could be conditioned immediately following containerisation and the final waste package interim stored pending GDF disposal. The benefits and limitations relating to the containerisation of pipes compared to the baseline PCM strategy are outlined in Table 12.

Table 12: Benefits and limitations of containerisation

Benefits	Limitations
The increased size of the container would result in fewer containers requiring interim storage.	If conditioning is deferred, a storage facility suitable for storing containerised (unconditioned) waste would be required.
Fewer containers would result in a reduced inspection and monitoring burden on the site during interim storage.	Larger containers may require a greater site infrastructure for effective handling.
A staged approach to containerisation means that the NDA's mission can be progressed - the management of pipes could progress with the containerisation of waste being undertaken even if the final treatment/ conditioning route has not been finalised.	

Treatment and conditioning

The conditioning approaches identified for pipes (Figure 5) include non-encapsulation, entombment, encapsulation and void filling. The benefits and limitations of each treatment and conditioning approach are summarised in Table 13.

Table 13: Benefits and limitations of treatment and conditioning

Benefits	Limitations
Non-Encapsulation	
A more cost effective option.	Potentially only suitable for a small number of packages e.g. packages containing waste with high corrosion resistance, good mechanical strength, low voidage and fixed activity.
High throughput route.	
Reduced operator exposure and intervention.	
Potentially suitable for packages containing pipes that have been pre-treated by compaction or cutting and display lower internal voidage.	
Non-encapsulation is likely to be compatible with pipes, which are predominately steel and hence display high corrosion resistance.	
Entombment	
Relatively high throughput.	Potentially only suitable for a small number of packages, such as those exhibiting low voidage (e.g. for compacted or cut pipes, thus removing voidage through increased packaging efficiency).
Potentially suitable for packages containing pipes that have been pre-treated by compaction or cutting and display lower internal voidage.	
Encapsulation	
Ensures that any mobile activity (e.g. residual particulate) on the pipework surfaces are immobilised.	May require the pipe walls to be disrupted for matrix in-fill.
In-fill of all voidage would be required for large bore pipes that have not been compacted or cut and have significant voidage.	Greater development work may be required to ensure that encapsulation has been successful and that the waste packages generated display the required characteristics e.g. low voidage.
Increased likelihood of waste packages being acceptable for future disposal.	Greater processing requirements and operator involvement.

Benefits	Limitations
Void Filling	
In-fill of all voidage would be required for large bore pipes that have not been compacted or cut and have significant voidage.	May require the pipe walls to be disrupted for the void filler to infiltrate into the void spaces.
Increased likelihood of waste packages being acceptable for future disposal.	Greater development work may be required to ensure that the void filling material has successfully infiltrated the waste and that the package displays the required characteristics e.g. low voidage.
	Void filling may reduce voidage and increase mechanical strength of the package, but it may not adequately fix mobile activity associated with pipes, or perform other functions that would render the waste package passively safe.
	Greater processing requirements and operator involvement.

6. Development of lifecycle RWMCs

The concept and intention of a lifecycle RWMC has been provided within the Introduction to this guidance and this section emphasises those areas which should be clearly presented to provide a justified overview of the proposed waste management process and the supporting justifying arguments.

The balance of risks across the lifecycle of the larger PCM waste item should be clearly presented in the RWMC indicating where decisions taken at one stage have a potential impact on other stages. As an example, the decision to store an unconditioned waste item for long term interim storage may have been based on existing financial restrictions recognising that the requirement for conditioning of the waste item, and subsequent costs and health and safety risks, will be placed on future working generations. The supporting BAT/BPM and ALARP assessments will be key references for these justifications and it should be clear within the RWMC the reasoning behind the decision to delay conditioning.

A demonstration of how knowledge retention will be achieved across the lifecycle should be presented in the RWMC. It is imperative that the knowledge behind why a waste item is being managed in a particular manner is adequately captured so that the residual risks and associated management steps have been considered and future working generations do not have the burden of a potential orphan waste item.

7. Summary

The management of larger PCM waste items will present its own range of challenges and opportunities for which a range of management solutions may be explored. This guidance presents waste packagers with information to support the development and implementation of their waste management strategies, recognising that for larger PCM waste items there will be areas of the waste packaging specifications for disposal which will be challenging to meet.

Due to the wide variety of forms of wastes and potential packaging methods, waste packagers are encouraged to discuss their detailed waste packaging plans with RWM at an early stage, in order to obtain independent advice on particular packaging proposals. RWM is prepared to give advice on specific applications, based on its knowledge of waste package behaviour during transport and the operational and post closure periods of a GDF, and from its experience obtained during the research and development of transport and disposal systems. The need for and acceptability of a relaxation of one or more wasteform performance requirements is determined as part of the disposability assessment.

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