Nuclear Waste Services

Review and update of the impact performance methodology for Robust Shielded Waste Packages

Task 1, 2 and 3

October 2021
Reference number: NWS-CR-23-008

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Preface

This work was originally contracted by Radioactive Waste Management (RWM). On 31 January 2022, RWM joined with Low Level Waste Repository and the Nuclear Decommissioning Authority's (NDA) Integrated Waste Management Programme, and is now part of a single organisation, called Nuclear Waste Services, within the NDA group.

Radioactive Waste Management (RWM) carries out research in support of geological disposal of the UK's higher activity radioactive waste. The work presented in this report forms part of our waste package accident performance research programme and was carried out by Jacobs, formerly Wood, formerly Amec Foster Wheeler, on our behalf. The work has been reviewed by RWM and by two independent peer reviewers. RWM accepts the data and conclusions in this report.

This document contains the following three reports on the subject of an impact methodology for robust shielded intermediate level waste (RSILW) packages:

Task 1 - Documentation and evaluation of methodology
(Jacobs, Review and update of the impact performance methodology for Robust Shielded Waste Packages: Task 1 – Documentation and evaluation of methodology, 208130/TR/001, Issue 3, 2021)

Task 2 - Update of methodology
(Jacobs, Review and update of the impact performance methodology for Robust Shielded Waste Packages: Task 2 – Update of methodology, 208130/TR/002, Issue 3, 2021)

Task 3 - Feasibility of a programme of research to further investigate RSILW package performance
(Jacobs, Review and update of the impact performance methodology for Robust Shielded Intermediate Level Waste (RSILW) packages: Task 3 – Feasibility of a programme of research to further investigate RSILW package performance, 208130/TR/003, Issue 3, 2021)

The first report in the suite provides a formal documentation and review of the methodology. A key finding was that there were aspects of the methodology that were potentially not conservative, not well underpinned, or superseded.

These issues are resolved in the second report, which addresses each of the concerns with the methodology and provides a suitably conservative solution, with clear options for including waste package specific data to take credit for extra performance if necessary.

The third report presents an investigation of feasible experimental projects that could be taken to reduce conservatisms or strengthen underpinning if required in the future.

In order to publish these three reports together, the conditions of publication pages (page 2 in each report) have been intentional removed in favour of a single shared conditions of publication page.

Review and update of the impact performance methodology for Robust Shielded Waste Packages: Task 1 – Documentation and evaluation of methodology

S Shah

Jacobs Report Reference	208130/TR/001
Partner References	ARUP/247318-08-01
Client Name	Radioactive Waste Management
Issue Number	Issue 3
Report Date	October 2021

DOCUMENT ISSUE RECORD

Document title	Review and update of the impact performance methodology for Robust Shielded Waste Packages: Task 1 – Documentation and evaluation of methodology
Project Reference	208130/TR/001

Issue	Description	Author	Checker	Approver	Approver	Date
Draft 1	For Wood comment	S. Shah (Arup)	C.F.Tso (Arup) C. Izatt (Arup)	C.F. Tso (Arup)		Oct 2018
Draft 2	Addressed comments from Wood. For comment by RWM	S. Shah (Arup)	C.F.Tso (Arup)	C.F. Tso (Arup)	R Mason (Wood)	Oct 2018
Draft 3	Addressed comments from RWM on Draft 2. For further comment by RWM	S. Shah (Arup)	C. Izatt (Arup)	C.F. Tso (Arup)	D Holton (Wood)	Mar 2019
Issue 1	Addressed comments from RWM on Draft 3. For peer review	S. Shah (Arup)	C. Izatt (Arup)	D. Gration (Arup)	D Lever (Wood)	May 2019
Issue 2	Addressed peer review comments on Issue 1	S. Shah (Arup)	C. Izatt (Arup)	D. Gration (Arup)	D Lever (Wood)	Aug 2019
Issue 3	Minor updates to references cited	S. Shah (Arup)	C. Izatt (Arup)	D. Gration (Arup)	K Butler (Jacobs)	Oct 2021

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ABSTRACT

A methodology for evaluating the release fractions (RFs) for Geological Disposal Facility (GDF) impact accident scenarios for robust shielded waste packages was developed by NDA in 2011. The methodology applies when gross structural integrity is demonstrably maintained during an impact accident scenario. It has been used to form the basis of Final stage Letter of Compliance (LoC) endorsement.

RWM has commissioned Arup, as subcontractors to Jacobs (formerly Wood Nuclear), to investigate the scientific underpinning of the methodology. The work has 3 tasks:

- Task 1: Documentation and Evaluation of Methodology;
- Task 2: Update of methodology;
- Task 3: Consider the feasibility of a programme of research to further investigate Ductile Cast Iron Container (DCIC) performance.

This report presents the work done under Task 1, which is to document and critically evaluate the methodology.

The RF methodology is broadly split into 5 steps. Each of these steps was evaluated by investigating the referenced sources and evaluating the scientific underpinning presented.

It is recognised that the methodology was based on information available at the time, and that a pragmatic approach was employed where there were gaps in the knowledge available to underpin the methodology. It has been found that the methodology does not take into account the appropriate physics of how particulates become airborne, it uses a scaling factor for drop height that is difficult to justify, scaling to sub-100 micron particulates is based on encapsulated wastes rather than unencapsulated waste, the calculation of package RF based on pressure difference simplifies the mechanism of release and further scientific underpinning is recommended over the particulate size distribution used to scale the package RF.

Many of the assumptions made could be revisited and revised. Some of the assumptions were found to be conservative, some were found to be unconservative and in some cases, further scientific underpinning is required to establish whether the assumption is either conservative or unconservative. The conclusion is that the methodology as it stands is “invalid”.

EXECUTIVE SUMMARY

A methodology for evaluating the release fractions (RFs) for Geological Disposal Facility (GDF) impact accident scenarios for Robust Shielded (RS) Intermediate Level Waste (ILW) Containers was developed by NDA in 2011. The methodology applies when gross structural integrity is demonstrably maintained during an impact accident scenario. It has been used to form the basis of Final stage Letter of Compliance (LoC) endorsement.

RWM has commissioned Arup, as subcontractors to Jacobs (formerly Wood Nuclear), to investigate the scientific underpinning of the methodology. The work has 3 tasks:

- Task 1: Documentation and Evaluation of Methodology;
- Task 2: Update of methodology;
- Task 3: Consider the feasibility of a programme of research to further investigate Ductile Cast Iron Container (DCIC) performance.

This report presents the work done under Task 1, which is to document and critically evaluate the methodology.

The RF methodology is broadly split into 5 steps:

- Step 1 – Assume a base RF value;
- Step 2 – Scale the base RF for required drop height;
- Step 3 – Scale the RF from Step 2 to the required particulate size;
- Step 4 – Scale the RF from Step 3, based on the difference in internal and external package pressures;
- Step 5 – Scale the RF from Step 4 based on wasteform particulate size distribution.

Each of these steps was evaluated by investigating the referenced sources and investigating the origins of the equations.

It is recognised that the methodology was based on information available at the time, and that a pragmatic approach was employed where there were gaps in the knowledge available to underpin the methodology. It has been found that the methodology does not take into account the appropriate physics of how particulates become airborne, it uses a scaling factor for drop height that is difficult to justify, scaling to sub-100 micron particulates is based on encapsulated wastes rather than unencapsulated waste, the calculation of package RF based on pressure difference simplifies the mechanism of release and further scientific underpinning is recommended over the particulate size distribution used to scale the package RF.

Many of the assumptions made could be revisited and revised. Some of the assumptions were found to be conservative, some were found to be unconservative and in some cases, further scientific underpinning is required to state whether the assumption is conservative or not. The conclusion is that the methodology as it stands is “invalid”.

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Glossary

Acronym	Definition
ARF	Airborne Release Fraction
BCD	Burst Cartridge Detection
BEIS	Department for Business, Energy and Industrial Strategy
CEC	Commission of the European Communities
CMP	Care and Maintenance Preparation
Cs	Caesium
DCIC(s)	Ductile Cast-Iron Container(s)
DNLEU	Depleted, Natural, and Low-Enriched Uranium
DSTS	Disposal System Technical Specification
DUO	Depleted Uranium Oxide
FED	Fuel Element Debris
F-ITEM	Fraunhofer Institute for Toxicology and Experimental Medicine
Fr	Froude number
GDF	Geological Disposal Facility
GNS	Gesellschaft für Nuklear-Service mbH
IEX	Ion Exchange Resin
LPF	Leak Path Factor
LSA	Low Specific Activity
ILW	Intermediate Level Waste
MAC	Miscellaneous Activated Components
MAR	Material At Risk
MCI	Miscellaneous Contaminated Items
MNOP	Maximum Nominal Operating Pressure
NDA	Nuclear Decommissioning Authority
PFA	Pulverised Fuel Ash
PIE	Post-Irradiation Examination
PPE	Personal Protective Equipment
PSD	Particulate Size Distribution
PSPILL	A proprietary programme coded using Fortran to calculate ARF for powders spilled from height

PWTP	Pond Water Treatment Plant
RF	Release fraction
RS	Robust Shielded
RWI	Radioactive Waste Inventory
RWM (formerly RWMD)	Radioactive Waste Management Limited (formerly Radioactive Waste Management Directorate)
SCO	Surface Contaminated Object
SCRU	Submersible Caesium Removal Unit
SLC	Site Licence Company
TiO_2	Titanium dioxide
WAC	Waste Acceptance Criteria

1 Introduction

The Nuclear Decommissioning Authority (NDA), through Radioactive Waste Management (RWM), is responsible for implementing UK Government policy for long-term management of higher activity radioactive wastes. Government policy for geological disposal of higher activity radioactive wastes, preceded by safe and secure interim storage, is set out in a policy paper by the Department for Business, Energy and Industrial Strategy (BEIS) [1].

As the implementer and future operator of a geological disposal facility (GDF), and therefore as the ultimate receiver of the waste for disposal, RWM will be responsible for the production of waste acceptance criteria (WAC) for the facility. While plans for the construction of a GDF remain at an early stage the information necessary to define WAC is not available. In the meantime, and as a precursor to the WAC, RWM produces packaging specifications and assesses packaging proposals from waste packagers with the aim of minimising the risk that conditioning and packaging of wastes will result in waste packages that are incompatible with the GDF. This is called the Disposability Assessment process.

The Disposability Assessment process typically follows a staged approach, based on an idealised packaging development project. The typical stages of the Disposability Assessment process are as follows:

- Conceptual stage – establish whether, in principle, the waste package is likely to be compliant with RWM requirements;
- Interim stage – establish whether the evidence allows demonstration that the as-designed waste packages are compliant with RWM requirements; and
- Final stage – determine whether the evidence allows demonstration that the waste packages as they would be manufactured would be compliant with RWM requirements.

Evidence to scientifically underpin the performance of these waste packages is required in order for the waste packages to be favourably assessed. At each stage, evaluations are performed in several technical areas in order to assess compatibility with the waste packaging specifications. One of these areas is the performance of the waste package during an impact accident scenario. Evaluating packages in this area requires the determination of a release fraction (RF) for the package, in order to determine the bounding releases expected in an impact accident scenario.

The concept of robust shielded (RS) waste packages is that the container is intended to provide the required performance, without having to rely on the properties of the wasteform. The Ductile Cast-Iron Containers (DCICs) proposed for use by Magnox are examples of RS waste containers. Two variants of RS waste containers currently have waste packaging specifications, and they are as follows:

- 500 litre robust shielded drum [2];
- 3 cubic metre robust shielded box [3].

RWM has accepted changes to the Disposal System Technical Specification (DSTS) to include 500 litre robust shielded drum packages based on the Gesellschaft für Nuklear-Service mbH (GNS) MOSAIK Type II container and 3 cubic metre robust shielded box based on the GNS Type VI container with the condition that the waste packages must be vented. Due to the possibility of corrosion and gas production within the waste, DCICs are expected to maintain a higher pressure than the outside environment, and the principal performance requirement of the vent is to keep this internal pressure below 1.5 bar absolute. As such, following an impact accident, there may be a pressure driven release of radioactive particulates from the DCICs if the seals fail. (Note that the DCICs may have vents and filters present, but these are not the assumed release path. The purpose of the filters is to prevent the gauge pressure inside the DCIC from exceeding 0.5 bar to ensure that the DCICs are not classed as pressure vessels under the PSSR regulations [4]).

A methodology to derive RFs of RS waste packages in GDF impact accident scenarios has been provided to Arup by RWM. The methodology has been adopted by a waste producer to derive the RF of their RS waste package.

RWM has commissioned Arup to review, potentially update, and document this methodology. The work is organised into three tasks:

- Task 1: Documentation and Evaluation of Methodology;
- Task 2: Update of methodology;
- Task 3: Consider the feasibility of a programme of research to further investigate DCIC performance.

Whether the work will proceed to Task 2 and Task 3 will depend on the outcome of Task 1.

This document presents our work in Task 1.

1.1 Objective

The objective for Task 1 is to document and evaluate the methodology, leading to three potential conclusions:

1. valid and up-to-date;
2. valid, but would be significantly improved using more recent data;
3. invalid.

1.2 Scope of Work

The scope of work for Task 1 is:

- to document and evaluate the current methodology for suitability for use in final stage Disposability Assessments, including examining relevant documents referenced by the methodology and how a waste producer has used the methodology;
- to consider the strengths and weaknesses of the methodology;
- to identify major areas of uncertainty and to identify knowledge gaps that may need to be filled;
- to conclude whether the methodology is valid and up-to-date, valid but would be significantly improved using more recent data or invalid.

As noted above, the methodology was provided to Arup by RWM. It was then adopted by a waste producer. Our evaluation is based on the methodology provided to us by RWM.

Comments on the differences between the methodology and how it was adopted by a waste producer are presented in Section 4.8 of this report.

It is noted that the original specification for Task 1 also stated that the potential to extend the methodology to a wider range of, if not all, waste package types containing unencapsulated wastes (such as Depleted, Natural, and Low-Enriched Uranium (DNLEU) wastes) should be considered. However, the outcome of the evaluation was such that this was not considered appropriate (see Section 4.9).

2 Robust Shielded Waste Packages

2.1 Robust Shielded Waste Containers

There are currently two RS waste containers that have waste package specifications defined: 500 litre robust shielded drum and 3 cubic metre robust shielded box. RWM confirmed at the kick-off meeting (held on 27th March 2018) that the specific waste containers to consider during this work are the GNS MOSAIK® Type II and the GNS Yellow Box® Type VI respectively.

2.2 Wastes contained within Robust Shielded Waste Containers

It is envisaged that RS waste containers will be used to package unencapsulated wastes. RWM commented that it is envisaged that the nature of the wastes in each RS waste container could be mixed. A summary of the wastes that could be placed within RS containers was supplied by RWM and is summarised in Table 1. In all these cases, the assumption is that the wastes are vacuum dried.

Table 1: Description of potential wastes packaged in RS waste containers

Waste	Description
Fuel Element Debris (FED) Metals	Fuel Element Debris (FED) Metals were produced as a result of fuel de-splittering operations across all seven sites and are dominated (on a mass/volume basis) by Magnox metal. Other constituents include stainless steel end caps, Nimonic springs and zirconium alloy bridges and pins. The category represents 48 UK Radioactive Waste Inventory (RWI) streams; a mixture of essentially non-porous activated metals with fuel-derived contamination, including reactive metal (Magnox) and some high dose items (stainless steel, Nimonic springs and zirconium).
FED Graphite	FED Graphite is limited to 5 UK RWI streams from Berkeley Power Station, again produced as a result of fuel de-splittering operations. In reality, this waste category is co-stored with FED metal. The range of porous graphite waste is likely to include almost whole struts, broken struts and fines, containing both activation products and fuel-derived contamination.
FED Nimonic	The FED Nimonic waste category, produced as a result of fuel de-splittering operations, comprises a single UK RWI stream of previously segregated Nimonic springs at Dungeness A. The category also reflects potential plans to segregate an additional 8 UK RWI streams from FED Metal at Hinkley Point A, Sizewell A and Oldbury. These are high dose items, dominated by activation products.

Waste	Description
Ion Exchange (IEX) Materials	The Ion Exchange (IEX) Materials waste category, 16 UK RWI streams produced by pond water or liquid effluent treatment at all sites except Sizewell A, comprises both inorganic and organic ion exchange materials; i.e. zeolite or predominantly phenol formaldehyde-based. The IEX materials are predominantly cationic, although some organic anionic resin was used in mixed beds. The activity on the IEX materials is dominated by Cs-137 with fuel-derived contamination also being present.
Sludge	The Sludge wastes comprise 36 UK RWI streams derived from a variety of processes at all sites except Sizewell A. Such processes include pond water treatment, active effluent treatment, pond sludge, filter pre-coat, pond skip decontamination and Magnox dissolution, including a range of contamination with oil. As such, the waste contains materials such as corrosion products of Magnox, sand, washings from changing rooms and laundries, diatomaceous earth, corrosion products of steels and carbonic acid-insoluble crud. Solids content, particle size and oil content of sludge will vary, as will the activity present in the form of activation and fuel-derived contamination.
Miscellaneous Contaminated Items (MCI)	The Miscellaneous Contaminated Items (MCI) waste category includes a diverse range of materials derived from a range of operational and CMP processes; 31 UK RWI streams from all seven sites. Processes that have generated MCI include general maintenance, laboratory operations including post-irradiation examination (PIE) of fuel and other items, gas circuit filtration and burst cartridge detection (BCD). Waste items include: • General trash such as rags, plastic wrappings and personal protective equipment (PPE) • PIE residues from Berkeley Centre, such as fuel pennies and sample residues, Magnox cladding and swabs • Maintenance trash such as pumps and pipe work • Filters and associated fines, including graphite fines in steel pots from Bradwell • Stainless steel BCD probes from Bradwell. Note that the waste is likely to contain activated items in addition to fuel- and core graphite-derived contamination.

Waste	Description
Miscellaneous Activated Components (MAC)	The Miscellaneous Activated Components (MAC) waste category comprises 7 UK RWI streams from Berkeley, Hinkley Point A and Chapelcross; a range of items that have been activated by irradiation within power reactors. Waste components include irradiated steels such as redundant control rods, charge chutes, refuelling machine components and thermocouples, irradiated graphite core samples (Berkeley Centre) and irradiated ceramic pellets from tritium isotope cartridges (Chapelcross Production Plant). There are also some miscellaneous Care and Maintenance Preparation (CMP) wastes such as vacuum bags and rags.
Gravel	Contaminated gravel from 24 UK RWI streams makes up the Gravel waste category; sites of origin are Berkeley, Bradwell, Hinkley Point A and Oldbury. The Gravel has arisen from the bottom of waste vaults and from pond wall scabbling operations. Physical/chemical contamination of the gravel is dominated by fines and small items from dry vault-stored wastes such as FED Metals and settled corrosion products from wetted wastes. As such, the activity may be in the form of activation and fuel-derived contamination.
Sand	There are 6 UK RWI streams in the Sand waste category; from Bradwell, Hinkley Point A and Sizewell A. This waste is predominantly from sand pressure filters used as part of pond water and effluent treatment systems. The nature of the contamination is dependent on how the sand filter was operated, but it is likely to be similar to the Sludge waste category and may contain oil contaminant.
Filters	The Filters waste category comprises a total of 10 UK RWI streams: • 4 Submersible Caesium Retrieval Unit (SCRU) pre-filters and 4 SCRU post-filter streams from Dungeness A, Hinkley Point A and Oldbury • A single Pond Water Treatment Plant filter stream from Hinkley Point A • A single Doulton filter stream from Dungeness A. The waste comprises mainly stainless steel and glass fibre. The activity on SCRU pre-filters will be pond sludge-derived (activation products and fuel-derived contamination) and the activity on the post-filters will be inorganic IEX material-derived (dominated by Cs-137). Activity on Pond Water Treatment Plant (PWTP) and Doulton filters will also be pond sludge-derived.
Cartridges	The Cartridges waste category comprised 5 UK RWI streams; SCRU IonSiv cartridges from Dungeness A, Hinkley Point A, Sizewell A and Oldbury. The 44 litre capacity cartridges contain the inorganic IEX material IonSiv IE911, essentially a titanium-substituted zeolite. Activity will be dominated by Cs-137, particularly where the IonSiv has been protected from pond sludge-derived contamination by a pre-filter.

3 Background and documentation of the methodology

3.1 Background

The principal aim of the Disposability Assessment process is to minimise the risk that the packaging of higher activity wastes, and any subsequent interim storage, results in waste packages being incompatible with geological disposal, as far as this is possible in advance of the availability of Waste Acceptance Criteria for a geological disposal facility (GDF). As such, it is an enabler for early hazard reduction on UK nuclear sites through facilitating packaging. One of the areas of assessment is the performance of waste packages during the GDF impact accident scenarios, the output of which is an RF, which will inform the safety cases.

When a waste producer first proposed to package wastes unencapsulated in DCICs, the concept was novel. While a methodology to derive RFs for waste packages with encapsulated wasteforms exists, it is not applicable to unencapsulated wasteforms.

It is understood that limited experimental data is available for DCICs and that no releases have been measured in those performed. Finite element (FE) analyses showed no breach through the body or lid in drops onto a flat yielding target, although a breach may occur in an aggressive feature impact. There is uncertainty in the performance of the seal at the time of a GDF impact accident, and how the pressurisation could cause a release.

RWM have provided a methodology, which is documented in this report, for estimating the RF from DCICs in impact accident scenarios.

3.2 Assumptions of methodology

There are three key assumptions in the methodology:

- The methodology can be used to calculate the sub-100 micron RF from a DCIC that is dropped;
- There is a separation between the performance of the wasteform and the DCIC waste container;
- There is some kind of breach in the lid seal. A predicted release fraction can only be greater than zero if there is a breach in the DCIC container. Depending on the scenario, the methodology identifies four possibilities: first the seals could hold giving rise to no release, second the seals could have already failed before the impact (i.e. impact with no pressurised contents), third the seals could fail completely with a sudden depressurisation or fourth a small leak path with a progressive depressurisation.

3.3 Documentation of the methodology

This section documents the methodology used to calculate RFs of RS waste packages, as provided to us by RWM.

The methodology has been used to calculate the RF based on sub-100 micron particulates in a 10.5 m drop onto a vault floor target, and a 9 m drop onto a DCIC which is positioned on the vault floor.

The methodology consists of five main steps:

Step 1. An RF of $2x10^{-3}$ from Section 4.2.2 of Commission of the European Communities (CEC) report, "*Improvement of the Radiological and Experimental Basis to Further Develop the Requirements of the IAEA Transport Regulations for LSA/SCO*[1] *Materials*" [5] (hereafter CEC report) is chosen as the "baseline" wasteform RF. The $2x10^{-3}$ value is an RF based on sub-10 micron particulates obtained from drop tests of Pulverised Fuel Ash (PFA) powder in various containers (e.g. paint tins) from a drop height of 9m.

Step 2. A scaling factor calculated using an algorithm (refer to Section 4.3) from Ballinger et al, "*Methods for Describing Airborne Fractions of Free Fall Spills of Powders and Liquids*" [6] is used to scale the baseline RF from Step 1 for different drop heights. If the drop height is 9m, then the RF from Step 1 is used without scaling.

Step 3. The RF from Step 2, which is based on sub-10 micron particulates, is scaled to become an RF for sub-100 micron particulates. A scale factor of $^{1}/_{0.106}$ is used and this is based on scale factors for cement encapsulated wastes from an Arup report, "*Derivation of Scaling Factor to Estimate the Mass of Particulates Smaller than 10 and 40 microns*" [7]. Noting that the resulting RF from Step 3 is still a "wasteform RF", i.e. the amount of particulate in the cavity of the RS container that is airborne and has the potential to be released through a breach or opening in the waste container.

Step 4. Package RF is calculated. It is assumed that the waste container is pressurised and the seal fails in some manner during the impact. The amount of particulates released is assumed to vary with a linear relationship between internal and external pressure (refer to Section 4.5). This is the DCIC_RF.

Step 5. Since the amount of sub-100 micron particulates in a waste is dependent on the particulate size distribution (PSD) of the waste, in this step, the DCIC_RF from Step 4 is multiplied by the mass percentage of sub-100 micron particulates of the waste in the container.

Each of these steps will be discussed and commented upon in Section 4.

[1] Low Specific Activity/Surface Contaminated Object

4 Evaluation of methodology

This section of the report postulates the physics of particulate release from a RS waste package in a drop impact event, and examines each step of the methodology.

4.1 Postulated physics of particulate release from a robust shielded waste package in an impact accident scenario

This section aims to postulate the physical behaviour of contents inside a DCIC waste package that is dropped.

When a RS waste package impacts a flat target, the outside of the waste container will deform locally where it bears onto the target, and the overall container will deflect slightly under its inertia. Knockback is expected to be small, the cavity of the waste container is not expected to suffer any permanent deformation, and the contents are not expected to be pushed or crushed by the deformation of the waste container.

During a drop, the RS waste container and its waste contents are subjected to acceleration due to gravity. The same acceleration is applied to the contents and waste container, including the air in any void in the cavity. There will not be any relative motion of air with the contents inside the cavity. This is similar to being a passenger in a car with the windows closed – the passenger does not experience any motion of air past them.

At the time the RS waste package impacts the target, the waste container will decelerate, whilst the contents will slump onto itself inside the cavity onto the lid or wall of the waste container that is immediately below it. If it is a loose particulate content, its own inertia under the deceleration will likely compact itself somewhat. Some of the kinetic energy of the contents will also be converted into internal energy as the contents deform and stop. Depending on the nature of the wasteform, some of it may breakup, and some finer particulates may be generated.

After the content has come to a stop, it will start to rebound. The rebound of the waste container will also give energy to the rebound of the contents. If the content consists of loose powder, the powder will splash into any voidage within the cavity, hitting the opposite walls and rebounding.

In order to have a release of the particulates from inside the cavity to the outside of the waste container, an opening must be available and a mechanism to move the particulates from the cavity through the opening must also be available. Even if an opening exists, particulates may be prevented from escaping due to blockages by particulates or larger waste items ahead of it, or due to settling over the tortuous path between the cavity and the exterior of the waste container. Smaller particulates may also clump together into larger sizes, making them too large for the opening.

In order to calculate the RF from RS waste packages, the mechanism to cause particulate generation and for particulates to become airborne in the cavity must be understood, a realistic path for release must be quantified, and a mechanism to drive the particulates through the opening must be understood.

4.2 Comments on Step 1

In Step 1, an RF of $2x10^{-3}$ from Section 4.2.2 of the CEC report [5] was chosen as the "baseline" wasteform RF. The $2x10^{-3}$ value is an RF based on sub-10 micron particulates obtained from drop tests of PFA powder in various containers (e.g. paint tins) from a drop height of 9m.

Section 4.2.2 of the CEC report [5] states:

> "*Drop tests performed within this study from 9 m height with Pulverised Fuel Ash (PFA) cement in different packagings (paint tin, can, cardboard box, plastic bag) revealed release fractions η_{10} from $2{\cdot}10^{-4}$ to $2{\cdot}10^{-3}$ depending on the degree of damage of the packaging*".

This paragraph is the source of the $2x10^{-3}$ baseline RF. It is the upper bound value of a range of RFs based on sub-10 micron particulates obtained from drop tests from 9m of "PFA cement" in different packagings (paint tin, can, cardboard box and plastic bag). The RF takes into account the containment provided by the packaging. Annex 2 of the CEC report [5] clarifies that "PFA cement" means PFA powder, with a particulate size range 0.9 - 175 microns. Note that it is "package RF", where "package" is PFA cement in paint tin, etc, but when used in the NDA memo, it is treated as a "wasteform RF".

The assumptions of adopting such a value of RF are:

- The baseline RF, based on PFA powders, is the same for all wasteforms;
- The mechanism of generating particulates is similar for all of the different wastes that will be placed inside DCICs;
- The baseline RF is "package" RF based on small-scale tests. The assumption is that this is appropriate as a basis for wasteform RF for a complete RS package.

One of the assumptions in Step 1 is that the baseline RF is constant for all wasteforms. Justification for this assumption is not apparent.

To establish whether this is reasonable, consider the PSD of different powder wastes. The typical size ranges for selected powdered wastes are given in Section A.2.2.3 of Annex 2 of the CEC report [5] and summarised in Table 2.

Table 2: Size Range of Powder Wastes (reproduced from Section A.2.2.3 of Annex 2 of [5]).

Material	Size Range (µm)
PuO_2	0.01 – 0.08
UO_2	0.032 – 0.85
U_3O_8	0.48 – 2.3

From this, it can be seen that the size of particulates in the powdered wastes in Table 2 is finer than the particulate size for PFA powder, which has a particulate size range 0.9 - 175 microns. Different powders have different PSDs.

Now consider whether different powders lead to a different “package” RF. Besides the drop tests of PFA cement in paint tins, etc, the CEC work also carried out drop tests of TiO_2 powder (which Sec A.2.2.3 of Annex 2 of the CEC report notes has a similar PSD as PuO_2 listed in the table above) in paint tins and cans. Lower package RFs were obtained from these drop tests of TiO_2 powder than the drop tests performed on PFA powder. Section 4.2.2 of the CEC report [5] states:

> “*The same drop tests with TiO_2 powder which is a very fine powder but considerably more adhesive showed release fractions more than two orders of magnitude lower.”*

This suggests that different powdered wasteforms will have different wasteform RFs. Therefore, the use of a single baseline RF in Step 1 to cover all wastes is a simplification. The categories of waste that will be placed inside DCICs are much wider than powdered wastes (as summarised in Section 2.2). The PSD for other types of waste, such as large sheets of metal, will not be the same as the PSD for PFA cement. The assumption that all of the wastes inside the DCIC will behave in a similar way to PFA cement is difficult to justify. Intuitively, a powdered wasteform with particulate size of the order of 100 microns would give the bounding wasteform RF. However, we do not know whether PFA powder has the highest PSD of sub-100 micron particulates and therefore the highest wasteform RF. Therefore, we cannot definitively state whether or not this is a conservative value to use, because there is not enough test data available for the wide range of wastes that will be packaged inside DCICs.

Another assumption adopted in Step 1 is that the “package” RF from the small-scale drop tests performed by CEC is appropriate as wasteform RF for RS waste package drops. But the behaviour of individual bags, tins and boxes being dropped onto a flat target will not be the same as the behaviour of wastes inside a RS waste package during an impact. The sizes are considerably different, and the “package” RF of the small-scale tests depends on the integrity of the container - plastic bags, tins and cardboard boxes. The packages provide partial confinement of the powder inside. If we examine existing data on PFA powders in “unconfined” glass specimens [8], the RF for a 9m drop appears to be in the range of $5x10^{-3}$ to $1x10^{-2}$, which is approximately a factor of 5 higher than the baseline RF in Step 1. Note that the technical paper [8] has not been comprehensively reviewed. Further investigation is required to establish whether the RF of $2x10^{-3}$ is a reasonable value to choose as a baseline wasteform RF.

It is noted that the value of $2x10^{-3}$ came from Section 4.2.2 of the CEC report [5]. However, later in the report, in Section 4.4, it gives “Proposed Release Fractions” of $5x10^{-3}$ for:

> “*solids, easily dispersible, e.g. powders, combustible with melting point < 300°C*”.

Regarding the use of an RF of $5x10^{-3}$, rather than $2x10^{-3}$, Section 4.4 of the CEC report [5] states:

> “*The values are considered as conservative, covering all experimental data available so far.*”

However, we do not consider it possible to establish how conservative a particular value of RF is, considering the drop tests did not represent a comprehensive full range of wastes that could be packaged.

In summary, using a single universal baseline RF is difficult to justify for all wasteforms and the use of a baseline RF of $2x10^{-3}$ is unlikely to be appropriate for the wide variety of wastes proposed to be packaged inside DCICs. Due to the uncertainty in this value, we cannot definitively state whether or not this is a conservative value to use, but it could potentially underestimate the baseline RF by a factor of 5. Further test data is required to establish whether this is appropriate for other wastes.

4.3 Comments on Step 2

The “package” RF from small scale tests in the CEC report that was adopted as wasteform RF in Step 1 was for a drop height of 9m. Step 2 applied a scale factor to scale the RF to different drop heights. The scale factor was calculated using an algorithm from Reference [6]. If the package RF that needs to be calculated is for a drop height of 9m, then the wasteform RF from Step 1 is used without scaling.

The methodology states: “*scale the height from 9 metres to 10.5 metres using the formula for height based on the ratio of 2.37 (see above) using a factor of 2.37*”.

The factor of 2.37 came from this formula:

“*For drop heights greater than 3 metres an algorithm is proposed in Annex 3:*

$$ARF = \frac{0.1064 \times M_0^{0.125} \times H^{2.37}}{\rho_{BP}^{1.02}}$$

Where M_0 *= mass of powder spilled, kg*

H = spill height, m

ρ_{BP} *= bulk density of powder, kg/m*^{3}.”

and ARF in the formula is Airborne Release Fraction.

That is, to scale the wasteform RF from 9m to 10.5m, a scale factor of $(10.5/9)^{2.37}$ was applied to the wasteform RF from Step 1.

The assumptions in Step 2 are:

- The algorithm is valid for drop heights greater than 3 metres, as specified in Reference [6].
- The algorithm is valid up to a 15m drop height.
- For a drop height of 9m, no height scaling is required because this was the drop height corresponding to the starting RF from Step 1.
- The algorithm is suitable for wasteforms inside DCICs.

The “Annex 3” in the above quotation refers to Annex 3 of the CEC report [5]. The algorithm originates from Sec 4.1 of NUREG/CR-4997 [6]. Section 4.0 of NUREG/CR-4997 [6] states:

“*This model is based on experimental results reported by Sutter et al. (1981)*”

The experimental data is reported in NUREG/CR-2139 [9] and was on tests performed on TiO_2 and DUO powder spills from drop heights of 1 m and 3 m. This is inconsistent with the statement from Annex 3 of the CEC report [5], which states:

"*For fall distances > 3 m the following algorithm for calculating the airborne release fraction developed by Ballinger et al. /BAL 88/ is proposed*"

(Note: /BAL 88/ is NUREG/CR-4997 [6])

The 3 m is therefore the upper limit of the range of spill heights in the experimental data on which the algorithm was based.

On examination of [6], the left hand side of the equation is given as F_r (note the subscript), not ARF. Fr (no subscript) is the standard terminology for Froude number, which is referred to earlier in Sec 4.1 of [6]. This is confusing. In this case, the full text says:

"*The fraction of powder made airborne as a result of these runs was statistically analyzed against the input values. The following algorithm was developed from this analysis and can be used in place of the code to predict the source term from powder spills if the air density and viscosity are 1.18 kg/m^3 and 1.85 x 10^{-5}, respectively.*

$$F_r = 0.1064 \frac{Mo^{0.125} H^{2.37}}{\rho^{1.02}} \qquad r^2 = 99.4\% \qquad (42)$$

As shown, the correlation coefficient was 99.4%, indicating a very strong correlation."

Confusingly, in the next Section in equation (43), the symbol for fraction airborne is changed to F. Considering it was published in 1988, there is no satisfactory way to confirm whether these were typological errors or indeed differing equation symbols. For the purposes of our evaluation, we assume that the left hand side is ARF as Annex 3 of the CEC report [5] interprets it.

NUREG/CR-4997 [6] states the following regarding the derivation of the algorithm:

"*The code was run with varying values for M_o…H… and ρ… The fraction of powder made airborne as a result of these runs was statistically analysed against the input values. The following algorithm was developed from this analysis and can be used in place of the code to predict the source term from powder spills if the air density and viscosity are 1.18kg/m^3 and 1.85E-05 respectively*".

"The code" is a programme named PSPILL, which is a bespoke Fortran programme, and its coding is included in the report. We do not have information about how robust the formulation and physics which have been built in the programme are. Therefore, we cannot evaluate if there are errors in the coding and if it was programmed incorrectly. Even if the physics represented are correct, the coding is correct and PSPILL does what it should do, it is for the modelling of spill of powder dropped through air from different drop heights, in which the interaction of the powder with air is a key factor in determining spillage. If a DCIC contains powder and the DCIC is dropped, the powder inside will not interact with air in the same way as powder spilled into air. The air in the cavity of the DCIC will be still (like the air in the compartment of a car). The physics of how particulates get "airborne" are completely different in the two scenarios. It is hard to see how the 2.37 factor in the algorithm can be applied to scale wasteform RF in a RS container to different heights.

The power factor of 2.37 also seems wrong in that when applied to different heights, the effect seems disproportionate to the change in drop height and energy. For example, raising the drop height from 9m to 10.5m increases the kinetic energy of the drop by approximately 17% (a factor of 1.17). But the scaling factor for RF with a power factor of 2.37 is $(10.5/9)^{2.37}$ = 1.44, i.e. wasteform RF for 10.5m drop would be higher than that for 9m drop by 44%. Conversely, if the drop height is reduced from 9m to say 7m, the scale factor is $(7/9)^{2.37}$ = 0.55. In this case, the kinetic energy of the drop has decreased by approximately 22%, but the wasteform RF has decreased by 45%. This is likely to be an underestimate and this treatment is therefore unconservative.

We also note that the height scaling power factor of 2.37 is significantly larger than the height scaling factor calculated from experimental data from R. Martens, et al, "*Experiments to Quantify Airborne Release from Packages with Dispersible Radioactive Materials under Accident Conditions*", EUROSAFE Forum 2005 [8]. Within this technical paper, experiments were performed on small glass containers, 200 litre drums and tin cans containing PFA or titanium oxide powders, which were dropped from various heights onto a flat target. The experiments on PFA inside glass containers (Figure 1) were considered by the paper's authors to be "unconfined" because the glass shattered completely when dropped, allowing the particulates to be released into the test chamber. Section 4 of this paper states:

> "*Up to a drop height of 15 m, the release fraction grows almost linearly with the drop height*".

The data and results presented in the paper have not described any experimental uncertainties. These should be investigated if the work is used to inform a change to the methodology. For scaling to higher drop heights, the RF would be less than that calculated by the methodology; for scaling to lower drop heights, the RF would be higher than that calculated by the methodology.

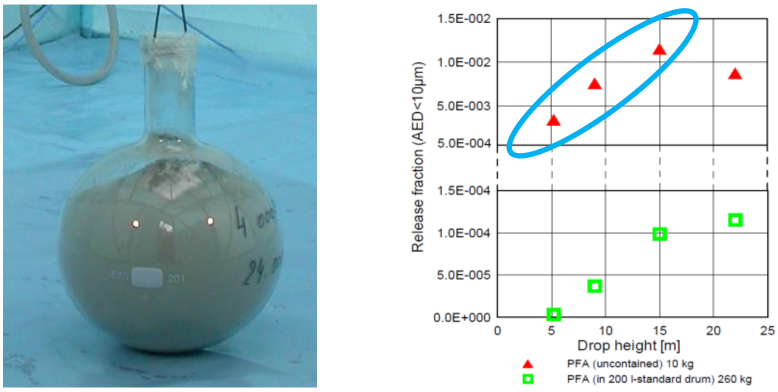

Figure 1: Glass container containing PFA powder used in experiments comparing RF from different drop height (from Fig 3.1 of [8]; results plot from Fig 4.3 of [8])

In summary, there is a significant difference in the mechanism for particulates to be airborne in a RS package during impact and the mechanism for powders spilled in air. We consider that the use of the algorithm based on powder spillage is not appropriate for scaling wasteform RF to height. The variation of RF from the small-scale tests on powders in glass specimens as quoted above from [8] may be a more appropriate means to scale RF with height. Assuming a linear scaling factor is more appropriate, using the methodology, scaling up from 9m to higher drop heights is likely to be conservative, but conversely, scaling down to lower drop heights is likely to be unconservative.

4.4 Comments on Step 3

The RF from Step 2 was for sub-10 micron particulates. In Step 3, this was scaled up by a factor of $^{1}/_{0.106}$ to calculate the RF for sub-100 micron particulates.

The scale factor was based on Arup report "*Derivation of Scaling Factor to Estimate the Mass of Particulates Smaller than 10 and 40 microns*" [7], which derived this value to scale the RF for encapsulated wastes based on sub-100 micron particulates to sub-10 and sub-40 micron particulates.

The assumptions in Step 3 are:

- The scale factor for encapsulated wasteform is the same as unencapsulated wasteform;
- The same scale factor is suitable for all wastes placed inside DCICs.

The $^{1}/_{0.106}$ factor was derived looking at the PSD of breakup of grout based wasteforms which break up during impact to generate particulates.

This factor is not applicable to the unencapsulated wastes that will be placed in DCICs.

Unencapsulated wastes will have an initial PSD before the impact. This PSD may alter during impact, due to crushing and abrasion between the particulates. But even if this is so, the mechanism and the resulting PSD will be different from the mechanism in which particulates are generated in cement encapsulated wasteforms.

Note that the methodology specifies a scale factor for scaling from sub-10 micron particulates to sub-100 micron particulates; but care must be taken and the scale factor should not be used in reverse to scale from sub-100 micron particulates to sub-10 micron particulates because this would not be conservative. This is because the scale factor chosen for scaling up from sub-10 to sub-100 micron particulates was the highest scale factor from the report referenced, leading to the highest sub-100 micron RF. If the same (highest) scale factor is used to scale from sub-100 to sub-10 micron particulates, this gives the lowest sub-10 micron RF, which is not conservative.

Also note that since the methodology was produced, RWM no longer requires the RF to be calculated for sub-100 micron particulates; instead, the RF is calculated based on sub-10 micron particulates [10]. In this case, the scaling in Step 3 is not required. A revised methodology may simply omit this step and therefore any conservatism does not come into play.

4.5 Comments on Step 4

In Step 4, the package RF ("*DCIC_RF*") is calculated. The approach is based on assuming that the DCIC waste package is pressurised and the seal fails during the impact. The amount of particulates released is assumed to vary with a linear relationship between internal and external pressure.

Step 4 uses an equation to estimate the package RF:

$$DCIC\_RF = \frac{ARF\ x\ (internal\ absolute\ pressure - external\ pressure)}{internal\ absolute\ pressure}$$

Where ‘external pressure’ means external absolute pressure.

The assumptions in Step 4 are:

- there is an opening in the DCIC;
- the package RF (DCIC_RF) is proportional to the pressure difference between the inside of the DCIC and atmospheric pressure outside;
- the internal maximum nominal operating pressure (MNOP) is 8 bar absolute.

Step 4 assumes the package RF (DCIC_RF) is proportional to the pressure difference between the inside of the DCIC and atmospheric pressure outside. The equation is simple and is based on static equilibrium (i.e. equalisation of pressure) between inside and outside the waste container. The methodology provides an example, which assumes a MNOP of 8 bar absolute to be the internal pressure in the DCIC. Nominally, the external pressure will be 1 bar absolute, hence the DCIC_RF = $^7/_8$ x (wasteform RF) from Step 3. This means that to reach equalisation of pressure, 7/8th of the gas inside the DCIC will escape and this will expel 7/8th of the airborne particulates inside the DCIC.

Note that the present specification for MNOP has been reduced from 8 bar absolute to 1.5 bar absolute. This means the scale factor changes from 7/8 to 1/3.

This part of the methodology does not postulate where the opening for release is or account for any blockage/holdup provided by restrictions in the release pathway. It also does not account for any clumping of particulates that may occur. It also does not account for the dynamics of gas flow, because the rate of release through an opening will vary during an impact, depending on the opening orifice size, the orifice shape, how long it remains open and the instantaneous pressure difference. There may also be a “spring-back” effect to reduce the seal opening orifice. Not taking into account blockage or containment factors is a conservative assumption. However, without further scientific underpinning, we cannot say whether or not the linear relationship is conservative. Indeed, it predicts zero RF for the case where the internal and external pressures are equal, which is not conservative, because even with zero pressure difference, assuming there is an opening, some particulates are expected to be expelled outwards.

In summary, step 4 presents a simplified equation for calculating the release from DCICs which does not take into account the opening, the release path, or the dynamics of the release. We also note the requirements for DCICs have changed and the MNOP is 1.5 bar (all DCICs will be vented). Without further scientific underpinning, we cannot say whether or not this step is conservative.

A more conservative and simpler approach could be to assume that all of the particulates that are available for release are released. This is consistent with the general approach for encapsulated waste. If all of the particulates generated are assumed to be released, the methodology could underestimate the RF by a factor of 3.

4.6 Comments on Step 5

In this step, the PSD of the waste is taken into account. To do so, the DCIC_RF from Step 4 is multiplied by the mass percentage of sub-100 micron particulates of the waste in the container. Since different wastes have differing PSDs, the scale factor applied in Step 5 should be based on the PSD of the specific waste that is proposed to be packaged inside the DCIC.

The methodology provides a specific example which assumed that the wasteform was entirely IEX resins.

> "*A particle size distribution is available for the Bradwell IEX material transferred to the storage vessel prior to 1977 and consisting predominantly of inorganic IEX. PSD data shows only 2.6wt% of the IEX material passed through a 100µm sieve.*
>
> *The available particulate (less than 100 microns) should be assumed to be 2.6%. This is reasonable within the bounds of data and information provided by the waste producer.*"

The example provided gives the PSD for Bradwell IEX material that is in a storage vessel and it is the PSD for waste that has not been involved in a drop from height. The calculation presented assumes the PSD of waste that has not been dropped is the same as the PSD of waste that has been dropped.

There is no evidence to underpin this assumption for powdered wastes. For example, consider a piece of dried sludge: in storage, it may have a PSD which shows all particulates are larger than 100 microns. However, after it is dropped, it may have been crushed by the content above, broken up into smaller pieces and generated sub-100 micron particulates. This is an area where further scientific underpinning would be beneficial to investigate how the PSD of non-powdered wastes changes before and after an impact. For waste such as dried sludge, the mass of sub-100 micron particulates generated after the drop could be orders of magnitude higher compared to the value before the drop, although we have not reviewed any test data to verify this.

In summary, we think Step 5 is likely to be unconservative, although we do not know the order of magnitude difference in RF calculated. The methodology in Step 5 would benefit from further scientific underpinning.

4.7 Summary of Evaluation

The methodology for calculating the package RF from DCICs contains 5 steps. The evaluation of each step is summarised in Table 3.

Table 3: Summary of Evaluation

Step	Summary of Evaluation
1	A baseline RF is proposed, which is the wasteform RF for sub-10 micron particulates for a drop height of 9m. This was selected from the RF of small-scale experiments performed on PFA powder inside plastic bags, tins and cardboard boxes which were detailed in the CEC report [5]. Using a single universal baseline RF is unlikely to be applicable for the wide variety of wastes to be packaged inside DCICs. Due to the uncertainty in this value, we cannot definitively state whether or not this is a conservative value to use. The RF from experimental data from tests on “unconfined” glass specimens containing PFA powder were approximately 5 times higher. This means the baseline RF proposed could be unconservative. This requires further investigation. Further test data is potentially required to establish whether this is appropriate for other wastes.
2	A scale factor was used for scaling to height. The scale factor was calculated using an algorithm based on powders free-falling through air from height and originating in [6]. The physics of powders free-falling through air are not the same as a powder in a DCIC that is dropped. Therefore, the use of the algorithm from [6] for scaling to height is not appropriate. Considering the physics is not correctly represented, the conservatism of this step cannot reasonably be justified. It is likely that scaling from 9m to higher drop heights is a conservative scaling factor, but scaling to lower drop heights is likely to give an unconservative scaling factor. It may be more appropriate to use the small-scale test data available in [8] to calculate the appropriate height scaling factor.
3	The sub-10 micron wasteform RF was scaled to a sub-100 micron wasteform RF. A factor of $^{1}/_{0.106}$ was used, based on the PSD of breakup of grout based wasteforms. This factor is not applicable to unencapsulated wastes, because they do not break up in the same physical manner as encapsulated wastes. We note that since the methodology was authored, the RF no longer needs to be calculated for sub-100 micron particulates but needs to be calculated for sub-10 micron particulates [10]. A revised methodology may simply omit this step and therefore any conservatism does not come into play.
4	An equation to estimate the package RF is used. The equation was based on the pressure difference between the inside and outside of the DCIC. The equation does not consider opening size, blockage, the release path or the dynamic effects of gas motion when particulates are released. Without further scientific underpinning, we cannot say whether or not this step is conservative. A more conservative and simpler approach could be to assume that all of the particulates that are available for release are released. If all particulates are assumed to be released, the RF from the methodology could be a factor of 3 times higher (assuming the waste package has an internal pressure of 1.5 bar).

Step	Summary of Evaluation
5	The DCIC_RF from Step 4 is multiplied by the mass percentage of sub-100 micron particulates of the waste contained inside the container, since different wastes will have a different PSD and hence a different amount of sub-100 micron particulates. An example for IEX resin assumes the PSD of waste that has not been dropped is the same as the PSD of waste that has been dropped. There is no evidence to underpin this assumption for powdered wastes. For waste such as dried sludge, the mass of sub-100 micron particulates generated after the drop could be orders of magnitude different compared to the value before the drop, although we have not reviewed any test data to verify this. The methodology in Step 5 would benefit from further scientific underpinning. We cannot definitively state whether Step 5 is conservative or not.

Overall, the calculation of release from a DCIC does not consider the physics of the release path and there is not sufficient scientific underpinning in the methodology. Additionally, some steps are inconsistent with other steps in terms of what waste is considered. The methodology is deemed to be "invalid". Some steps are likely to be conservative, other steps are potentially unconservative and some steps require further work to understand the level of conservatism. Although we have made comments on the conservatism of individual steps, it is difficult to define the overall level of conservatism in the methodology.

4.8 Comments on waste producer example use of the RF methodology

A waste producer has followed the RF methodology documented in this report in Section 3. It was noted that the methodology used by the waste producer was the same as that documented in Section 3, although there were some differences in the scale factors assumed. These differences are reviewed in this section.

- In Step 3, in which the RF based on sub-10 micron particulates was scaled to the RF based on sub-100 micron particulates, the waste producer did not use a scale factor of $^1/_{0.106}$ as specified in 3.3. Instead, a factor of $^1/_{0.3}$ was used instead. This was explained as follows:

  > *"Reference [22] summarises the results from experiments in which quantities of uncontained pulverised fuel ash (PFA) and TiO_2 powders were dropped from heights of between 5 and 20m, and the resultant airborne fractions collected and quantified. Around 30 wt% of the PFA comprised particles <10 µm.*"
  >
  > (Reference 22 is [8])

  The scaling factor of 30% used by the waste producer is based on the PSD of PFA powder. To understand whether this scaling factor is appropriate, Annex 2 of the CEC report [5] states that PFA powder has a particulate size range 0.9 - 175 microns. 30% of the particulates were sub-10 micron and all particulates were sub-175 microns. Scaling by $^1/_{0.3}$ gives the RF of sub-175 micron particulates. How the PSD varies between sub-100 microns and sub-175 microns was not documented in the CEC report [5] but the scaling factor for sub-175 microns will be larger than sub-100 microns and is conservative.

The waste producer used a scale factor based on small-scale tests on powders rather than the methodology in Section 3.3, which uses a scale factor based on cement encapsulated wastes. The approach taken by the waste producer seems to be more appropriate for powdered wastes than the methodology in Section 3.3, because the methodology's scale factor is based on encapsulated waste and not powdered wastes.

However, the wasteform in this case is Dungeness A IEX resin. This waste is not the same as powder. Therefore, we have reservations about using the methodology to calculate scaling factor for non-powdered wastes.

- In Step 5, the waste producer appears to use a mass percentage of sub-100 micron particulates, which is based on a different waste to the example given in the Section 4.6. The value of 0.01% was used, based on the mass percentage of sub-100 micron particulates of Dungeness A IEX resin stored in Settling Tank 3 (ST3) and Settling Tank 4 (ST4).

  The value used by the waste producer is based on samples of IEX resin taken from ST3 which contains the waste that will be packaged. ST3 contains two different types of IEX resin: "Lewatit DN" and "Duolite ARC 9359". Samples of both IEX resins were obtained, as described by the waste producer:

  "*The bulked samples were also analysed for particle size distribution (PSD), with consistent results observed between resin types. Sieving results indicate that >99 wt% was sub-1.7mm and particle size distribution data show around 10 vol% was sub-500 µm, with <0.01% sub-275 µm.*"

  The waste producer assumes:

  "*For the purpose of assessment, RWM has assumed that 0.01% of the mass of IEX resin has sub-100µm particle size.*"

  There is ambiguity regarding whether the values provided are vol% or wt%. The mass percentage of sub-100 micron particulates assumed is based on the waste that will be packaged, and appears consistent with Step 5 of the methodology (see Section 3.3). However, we note that only samples from ST3 were taken. It would be beneficial to obtain samples from all of the wastes to determine an appropriate value of the mass percentage of sub-100 micron particulates.

- RWM also performed a "sensitivity" study on the calculation of RF. RWM stated:

  "*This sensitivity analysis is based upon a bounding assumption that 100% of the radionuclide content is in respirable particulate form, thereby increasing the above RFs by a factor of ten thousand*."

  This means that in Step 5, instead of assuming that "*0.01% of the mass of IEX resin has sub-100µm particle size"*, the sensitivity study assumes 100 % of the mass of IEX resin has sub-100 µm particulate size. The sensitivity assumption is conservative for this step of the methodology.

4.9 Extension of methodology to a wider range of waste package types and wastes

Considering the methodology has been evaluated and deemed “invalid”, it follows that extending it to a wider range of wastes, such as DNLEU wastes is not appropriate. Extending the methodology to all waste package types containing unencapsulated wastes is similarly not appropriate.

Assuming that future work develops a valid methodology, to extend such a revised methodology to a wider range of waste packages and wastes, the following knowledge gaps need to be filled:

- RS containers are assumed not to have any significant change in internal volume or breach of the container. To extend the methodology to other waste packages, any changes to these assumptions need to be addressed, e.g. if the waste package deforms.
- If there is internal deformation of the container, the effect on the wasteform may need to be considered.
- If the deformation leads to breaches in the container (i.e. other than the seal), these release pathways need to be taken into account.
- There is limited data related to the characterisation of the wide variety of waste that will be placed in RS containers. Testing and characterisation of a broader range of wastes is suggested (e.g. measurement of PSD).
- The method for scaling to height requires reconsideration, perhaps through use of more appropriate existing drop test data or through a new, bespoke drop test programme.
- The methodology assumes that a pressure difference between inside and outside the cavity leads to release and the release is proportional to the pressure difference. There is potential to provide further scientific underpinning to this step. The case where there is no pressure difference also requires consideration.

Future work may be able to encompass all types of unencapsulated wastes and all types of waste container for unencapsulated wastes. Alternatively, it may be that different wastes/waste containers are grouped into sub-categories and a unique methodology applied to each sub-category of waste package/waste category.

5 Conclusions

A methodology to calculate the RF from DCIC was provided by RWM. This report has documented and reviewed the methodology. The methodology has 5 steps:

- In Step 1, a baseline RF was selected, based on small-scale tests performed on PFA powder inside plastic bags, tins and cardboard boxes and which were reported in the CEC report [5]. The baseline RF was a wasteform RF for sub-10 micron particulates. The use of a single baseline RF to cover all wastes is difficult to justify, because different wastes would lead to different wasteform RFs. The RF from experimental data from tests on “unconfined” glass specimens containing PFA powder were approximately 5 times higher. This means the baseline RF proposed could be unconservative. This requires further investigation. Further test data is potentially required to establish whether this is appropriate for other wastes.
- In Step 2, an algorithm was used calculate a scale factor to scale the wasteform RF from Step 1 from a drop height of 9m to a drop height of 10.5m. This was suitable for drop heights up to 15m. We consider that the use of the algorithm based on powder spillage in air is not appropriate for scaling wasteform RF to height. Considering the physics is not correctly represented, the conservatism of this step cannot reasonably be justified. It is likely that scaling from 9m to higher drop heights is a conservative scaling factor but scaling to lower drop heights will give an unconservative scaling factor. The use of data from other relevant small-scale tests on powders may be a more appropriate means to scale RF with height.
- The wasteform RF from Step 2 was based on sub-10 micron particulates. In Step 3, this was scaled to a sub-100 micron wasteform RF. A scale factor of $^{1}/_{0.106}$ was used, based on the PSD of breakup of grout based wasteforms. This factor was not applicable to unencapsulated wastes. We note that presently, the RF no longer needs to be calculated for sub-100 micron particulates but needs to be calculated for sub-10 micron particulates. A revised methodology may simply omit this step and therefore any conservatism does not come into play.
- Step 4 calculated the package RF using an equation that considered the pressure difference between the pressure inside the DCIC and the external pressure. This equation was based on a MNOP of 8 bar (unvented DCICs). The equation does not consider opening size, blockage or the path that particulates take before they can be released. It ignores the release path for particulates. We also note the requirements for DCICs have changed and the MNOP is 1.5 bar (all DCICs will be vented). Without further scientific underpinning, we cannot say whether or not this step is conservative. A more conservative and simpler approach could be to assume that all of the particulates that are available for release are released. If all particulates are assumed to be released, the RF from the methodology could be a factor of 3 times higher (assuming the waste package has an internal pressure of 1.5 bar).
- In Step 5, the DCIC_RF from Step 4 is multiplied by the mass percentage of sub-100 micron particulates of the waste contained inside the container, which is obtained from the PSD of the waste being packaged. This assumes the PSD of waste that has not been dropped is the same as the PSD of waste that has been

dropped. We are unsure if this is a reasonable assumption for non-powdered wastes. For waste such as dried sludge, the mass of sub-100 micron particulates generated after the drop could be orders of magnitude different compared to the value before the drop, although we have not reviewed any test data to verify this. The methodology in Step 5 would benefit from further scientific underpinning. We cannot definitively state whether Step 5 is conservative or not.

A waste producer has adopted the methodology to calculate the RF for a DCIC. Some differences in the scale factors were found, but the methodology used was consistent with the methodology documented in this report.

It is recognised that the methodology was based on information available at the time, and that a pragmatic approach was employed where there were gaps in the knowledge available to underpin the methodology. It has been found that the methodology does not take into account the appropriate physics of how particulates become airborne, it uses a scaling factor for drop height that is difficult to justify, scaling to sub-100 micron particulates is based on encapsulated wastes rather than unencapsulated waste, the calculation of package RF based on pressure difference simplifies the mechanism of release and further scientific underpinning is recommended over the PSD used to scale the package RF.

Many of the assumptions made could be revisited and revised. The conclusion is that the methodology as it stands is “invalid”. Some steps are likely to be conservative, other steps are potentially unconservative and some steps require further work to understand the level of conservatism. Although we have made comments on the conservatism of individual steps, it is difficult to define the overall level of conservatism in the methodology.

Considering the methodology has been evaluated and deemed “invalid”, it follows that extending it to a wider range of wastes, such as DNLEU wastes is not appropriate. Assuming that future work develops a valid methodology, to extend such a revised methodology to a wider range of waste packages and wastes, the following knowledge gaps need to be filled:

- RS containers are assumed not to have any significant change in internal volume or breach of the container. To extend the methodology to other waste packages, any changes to these assumptions needs to be addressed, e.g. if the waste package deforms.
- If there is internal deformation of the container, the effect on the wasteform may need to be considered.
- There is limited data related to the characterisation of the wide variety of waste that will be placed in RS containers. Testing and characterisation of a broader range of wastes is suggested (e.g. measurement of PSD).
- The method for scaling to height requires reconsideration, perhaps through use of more appropriate existing drop test data or through a new, bespoke drop test programme.
- The methodology assumes a pressure difference between inside and outside the cavity leads to release and the release is proportional to the pressure difference. There is potential to provide further scientific underpinning to this step. The case where there is no pressure difference also requires consideration.

6 References

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Review and update of the impact performance methodology for Robust Shielded Waste Packages: Task 2 – Update of methodology

S Shah

Jacobs Report Reference	208130/TR/002
Partner References	ARUP/247318-13
Client Name	Radioactive Waste Management Limited
Issue Number	Issue 3
Report Date	October 2021

DOCUMENT ISSUE RECORD

Document title	Review and update of the impact performance methodology for Robust Shielded Waste Packages: Task 2 – Update of methodology
Project Reference	208130/TR/002

Issue	Description	Author	Checker	Approver	Approver	Date
Draft 1	For Jacobs comment	S. Shah (Arup)	C. Izatt (Arup)	D. Gration (Arup)		Feb 2020
Draft 2	For RWM review	S. Shah (Arup)	C. Izatt (Arup)	D. Gration (Arup)	D. Holton (Jacobs)	Feb 2020
Issue 1	Updated in response to RWM review comments	S. Shah (Arup)	C. Izatt (Arup)	D. Gration (Arup)	R. Thetford (Jacobs)	Oct 2020
Issue 2	Updated in response to Peer review comments	S. Shah (Arup)	C. Izatt (Arup)	D. Gration (Arup)	D. Lever (Jacobs)	Mar 2021
Issue 3	Minor updates to references cited	S. Shah (Arup)	C. Izatt (Arup)	D. Gration (Arup)	K. Butler (Jacobs)	Oct 2021

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ABSTRACT

A methodology for evaluating the Release Fractions (RFs) for Geological Disposal Facility (GDF) impact accident scenarios for Robust Shielded (RS) Intermediate Level Waste (ILW) Containers was provided to Arup by RWM. The methodology applies when gross structural integrity of the waste container is demonstrably maintained during an impact accident scenario. It has been used to form the basis of a Final stage Letter of Compliance (LoC) endorsement.

In Task 1, the methodology was documented and critically evaluated. It was recognised that the methodology was based on the information available at the time and that a pragmatic approach was employed where there were knowledge gaps. However, the conclusion to Task 1 was that some parts of the methodology were not appropriately underpinned or did not contain appropriate conservatisms.

This report presents the work done under Task 2. The methodology has been updated using existing knowledge, with each stage having appropriate scientific underpinning. The revised methodology has 4 stages:

- Stage 1: Start with a baseline wasteform RF of 1.8×10^{-2}, which is the wasteform RF for sub-10 micron particulates for a drop height of 9 m.
- Stage 2: Scale the baseline wasteform RF linearly from a drop height of 9 m to the required drop height.
- Stage 3: Obtain the proportion of sub-10 micron particulates from the particulate size distribution (PSD) and use this to scale the wasteform RF to take into account the type of wasteform stored. If the PSD is not available, the scale factor should be assumed to be 1.
- Stage 4: The package RF is calculated by assuming the release of particulates is caused by a pressure gradient between the inside and outside of the package, generating a flow of airborne particulates through an opening in the lid-body gap. A minimum internal gauge pressure of 0.5 bar should be assumed for the calculation.

EXECUTIVE SUMMARY

A methodology for evaluating the Release Fractions (RFs) for Geological Disposal Facility (GDF) impact accident scenarios for Robust Shielded (RS) Intermediate Level Waste (ILW) Containers was provided to Arup by RWM. The methodology applies when gross structural integrity of the waste container is demonstrably maintained during an impact accident scenario. It has been used to form the basis of a Final stage Letter of Compliance endorsement.

Radioactive Waste Management Ltd (RWM) commissioned Arup, as subcontractors to Jacobs (formerly Wood Nuclear), to investigate the scientific underpinning of the methodology. The work has 3 tasks:

- Task 1: Documentation and evaluation of the methodology;
- Task 2: Update of the methodology;
- Task 3: Consider the feasibility of a programme of research to further investigate Robust Shielded Container (RSC) performance.

In Task 1, the methodology was documented and critically evaluated. It was recognised that the methodology was based on the information available at the time and that a pragmatic approach was employed where there were knowledge gaps. However, the conclusion to Task 1 was that some parts of the methodology were not appropriately underpinned or did not contain appropriate conservatisms.

This report presents the work done under Task 2, which is to update the methodology using existing knowledge to ensure that each stage has appropriate scientific underpinning.

The revised methodology has 4 stages:

- Stage 1: Start with a baseline wasteform RF of 1.8×10^{-2}, which is the wasteform RF for sub-10 micron particulates for a drop height of 9 m.
- Stage 2: Scale the baseline wasteform RF linearly from a drop height of 9 m to the required drop height.
- Stage 3: Obtain the proportion of sub-10 micron particulates from the particulate size distribution (PSD) and use this to scale the wasteform RF to take into account the type of wasteform stored. If the PSD is not available, the scale factor should be assumed to be 1.
- Stage 4: The package RF is calculated by assuming the release of particulates is caused by a pressure gradient between the inside and outside of the package, generating a flow of airborne particulates through an opening in the lid-body gap. A minimum internal gauge pressure of 0.5 bar should be assumed for the calculation. Assuming the internal gauge pressure is 0.5 bar, the package RF equals the wasteform RF multiplied by $^{1}/_{3}$.

The revised methodology is scientifically underpinned and is therefore recommended as a replacement for the previous methodology. It is recognised that the revised methodology will produce higher package RFs than the previous methodology as it is more conservative overall. These conservatisms could be reduced with further research and testing, which will be considered further in Task 3.

There is good potential to extend the methodology to a wider range of waste packages containing unencapsulated waste, e.g. UILW packages containing entombed waste or a waste package that has corroded pockets of entombed waste inside an encapsulated waste matrix. Some modifications to Stage 4 would be necessary to account for differences in the amount of release from the waste package and this would be done on a case-by-case basis.

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Glossary

Acronym	Definition
ARF	Airborne Release Fraction
BEIS	Department for Business, Energy and Industrial Strategy
CEC	Commission of the European Communities
DCIC	Ductile Cast-Iron Container
DNLEU	Depleted, Natural and Low-Enriched Uranium
DSTS	Disposal System Technical Specification
F-ITEM	Fraunhofer Institute for Toxicology and Experimental Medicine
GDF	Geological Disposal Facility
GNS	Gesellschaft für Nuklear-Service mbH
IEX	Ion Exchange Resin
ILW	Intermediate Level Waste
LSA	Low Specific Activity
NDA	Nuclear Decommissioning Authority
NUREG	(United States) Nuclear Regulatory Commission (Report)
PFA	Pulverised Fuel Ash
PSD	Particulate Size Distribution
PSSR	Pressure Systems Safety Regulations
RF	Release Fraction
RS	Robust Shielded
RSC	Robust Shielded Container
RSILW	Robust Shielded Intermediate Level Waste
RWM (formerly RWMD)	Radioactive Waste Management Limited (formerly Radioactive Waste Management Directorate)
TiO_2	Titanium dioxide
UILW	Unshielded Intermediate Level Waste
WAC	Waste Acceptance Criteria

1 Introduction

1.1 Background

The Nuclear Decommissioning Authority (NDA), through Radioactive Waste Management (RWM), is responsible for implementing UK Government policy for long-term management of higher activity radioactive wastes. Government policy for geological disposal of higher activity radioactive wastes, preceded by safe and secure interim storage, is set out in a policy paper by the Department for Business, Energy and Industrial Strategy (BEIS) [1].

As the implementer and future operator of a geological disposal facility (GDF), and therefore as the ultimate receiver of the waste for disposal, RWM will be responsible for the production of waste acceptance criteria (WAC) for the facility. While plans for the construction of a GDF remain at an early stage, the information necessary to define WAC is not available. In the meantime, and as a precursor to the WAC, RWM produces packaging specifications and assesses packaging proposals from waste packagers with the aim of minimising the risk that conditioning and packaging of wastes will result in waste packages that are incompatible with the GDF. This is called the Disposability Assessment process.

The Disposability Assessment process typically follows a staged approach, based on an idealised packaging development project. The typical stages of the Disposability Assessment process are as follows:

- Conceptual stage – establish whether, in principle, the waste package is likely to be compliant with RWM requirements;
- Interim stage – establish whether the evidence allows demonstration that the as-designed waste packages are compliant with RWM requirements; and
- Final stage – determine whether the evidence demonstrates that the as manufactured waste packages would be compliant with RWM requirements.

Evidence to scientifically underpin the performance of these waste packages is required in order for the waste packages to be favourably assessed. At each stage, evaluations are performed in several technical areas in order to assess compatibility with the waste packaging specifications. One of these areas is the performance of the waste package during an impact accident scenario. Evaluating packages in this area requires the determination of a Release Fraction (RF) for the package, in order to determine the bounding releases expected in an impact accident scenario.

The concept of Robust Shielded (RS) waste packages is that the container is intended to provide the required performance, without having to rely on the properties of the wasteform. The Ductile Cast-Iron Containers (DCICs) proposed for use by Magnox are examples of RS containers (RSCs)[1]. Two variants of RSC currently have waste packaging specifications, these are:

- 500 litre robust shielded drum [2];

[1] RSCs can be considered a broader term, encompassing DCICs. However, for the purpose of this document, the terms are essentially interchangeable.

- 3 cubic metre robust shielded box [3].

RWM has accepted changes to the Disposal System Technical Specification (DSTS) to include 500 litre robust shielded drum packages based on the Gesellschaft für Nuklear-Service mbH (GNS) MOSAIK Type II container and 3 cubic metre robust shielded box based on the GNS Type VI container with the condition that the waste packages must be vented. Due to the possibility of corrosion and gas production within the waste, DCICs are expected to maintain a higher pressure than the outside environment, and the principal performance requirement of the vent is to keep this internal pressure below 0.5 bar gauge. As such, following an impact accident, there may be a pressure driven release of radioactive particulates from the DCICs if the seals fail (Note that the DCIC vents and filters are not the assumed release path. The purpose of the vents is to prevent the gauge pressure inside the DCIC from exceeding 0.5 bar to ensure that the DCICs are not classed as pressure vessels under the Pressure Systems Safety Regulations (PSSR) [4]).

A methodology to derive RFs for RSCs in GDF impact accident scenarios has been provided to Arup by RWM. The methodology has been adopted by a waste producer to derive the RF of their RSC.

RWM has commissioned Arup, as subcontractors to Jacobs (formerly Wood Nuclear), to review, update, and document this methodology. The work is organised into three tasks:

- Task 1: Documentation and evaluation of the methodology;
- Task 2: Update of the methodology;
- Task 3: Consider the feasibility of a programme of research to further investigate RSC performance.

The methodology was documented and critically evaluated in Task 1 [5]. It was recognised that the methodology was based on the information available at the time and that a pragmatic approach was employed where there were knowledge gaps. However, the conclusion to Task 1 was that some parts of the methodology were not appropriately underpinned or did not contain appropriate conservatisms.

1.2 Objective and Scope

The objective of Task 2 is to produce a valid RF methodology using existing knowledge to ensure that each stage has appropriate scientific underpinning.

The scope of work for Task 2 is:

- Use existing data to update the methodology where weaknesses were identified in Task 1;
- Develop a "valid" methodology that can be applied to estimate the RF from Robust Shielded Intermediate Level Waste (RSILW) packages;
- Identify whether major areas of uncertainty or knowledge gaps remain in the methodology that could be investigated in Task 3;
- Consider the potential to extend the revised methodology to a wider range of, if not all, waste package types containing unencapsulated wastes (such as Depleted, Natural, and Low-Enriched Uranium (DNLEU) wastes);

The update to the methodology has used information from the references summarised in Table 1.

Table 1: Summary of References Used in Updating the Methodology

References	Reference
CEC, *Improvement of the Radiological and Experimental Basis to Further Develop the Requirements of the IAEA Transport Regulation for LSA/SCO Materials, Final Report*, Commission of European Communities, Contract No. 4.1020/D/01-001, LL19042860, 2005.	[6]
Fraunhofer ITEM, *Determination of Breakup and Airborne Release for different Cemented Materials when subject to Mechanical Impact for United Kingdom Nirex Limited*, Fraunhofer-ITEM Report: 1129331, September 2005.	[7]
Pacific Northwest Laboratory (S. L. Sutter, J. W. Johnston, J. Mishima), *Aerosols Generated by Free Fall Spills of Powders and Solutions in Static Air*, NUREG/CR-2139, December 1981.	[8]
R. Martens, F. Lange, W. Koch and O. Nolte, *Experiments to Quantify Airborne Release from Packages with Dispersible Radioactive Materials under Accident Conditions*, [In]: U. Erven (ed), EUROSAFE Forum 2005: Safety Improvements – Reasons, Strategies, Implementation, Brussels, 7 - 8 November 2005.	[9]
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GRS, *Analyse der Sicherheit bei der Beförderung und Lagerung radioaktiver Stoffe – Quantifizierung der Freisetzung bei Transportund Handhabungsunfällen (Analysis of safety during transportation and storage radioactive substances* - *Quantification of Release at Transport and handling accidents)*, Order No: 854600, July 2005.	[11]
Lange, F., Martens, Nolte, O., Lodding, H., Koch, W. and Hörmann, E., *Testing of packages with LSA materials in very severe mechanical impact conditions with measurement of airborne release*, J. Packaging, Transport, Storage and Security of Radioactive Materials vol 18 No. 2 pg 59-71, 2007	[12]

2 Summary of Evaluation of Previous RF Methodology

The previous methodology for calculating the package RF from DCICs contains 5 steps. A summary of the steps and the evaluation from the Task 1 report [5] is given in Table 2. Further details can be found in [5], including a more detailed summary in Table 3 of that report.

Table 2: Summary of evaluation of the previous RF methodology

Step	Summary of Evaluation
1	Sets a baseline RF for sub-10 micron particulates for a drop height of 9 m based on "confined powder" experiments. The evaluation considers that this is unlikely to bound the wide variety of wastes to be packaged inside Ductile Cast Iron Containers (DCICs); hence it cannot be definitively stated as conservative. In fact, since experimental data from tests on "unconfined" glass specimens have higher RFs, the baseline wasteform RF could be unconservative and should be revisited.
2	A scale factor is used for scaling to height. The scale factor is calculated using an algorithm based on powders free-falling through air from height (originating in [10]). The evaluation considers this algorithm, as applied, to be inappropriate and suggests alternative data upon which to base the scaling factor.
3	The sub-10 micron wasteform RF was scaled to a sub-100 micron wasteform RF [13]. However, since the methodology was authored, the RF no longer needs to be calculated for sub-100 micron particulates; hence any revised methodology can omit this step [14].
4	An equation to estimate the package RF (DCIC_RF) is used, based on the pressure difference between the inside and outside of the DCIC. Further scientific underpinning would be of benefit to determine whether this step is conservative. $$DCIC\_RF = \frac{ARF \times (internal\ absolute\ pressure - external\ pressure)}{internal\ absolute\ pressure}$$
5	The package RF from Step 4 is multiplied by the mass percentage of sub-100 micron particulates of the waste contained inside the container, since different wastes will have a different Particle Size Distribution (PSD). The evaluation concludes there is no evidence to underpin this approach for powdered wastes and that further scientific underpinning is required, or that a bounding approach be used.

The conclusion from the Task 1 report [5] was that some parts of the methodology were not appropriately underpinned or did not contain appropriate conservatisms. However, it is recognised that the approach taken was pragmatic and utilised the experimental data available. In reaching this conclusion, the following observations were made:

- Calculation of release from a DCIC does not consider the physics of the release path;
- There is insufficient scientific underpinning in the methodology;
- Some steps are inconsistent with other steps in terms of what waste is considered;
- It is difficult to define the overall level of conservatism in the methodology because some steps are potentially unconservative (Step 1) and some steps require further work to understand the level of conservatism (Steps 4, 5).

3 Revised Methodology

3.1 Introduction

This section describes work done to modify and update the methodology so that it is valid, scientifically underpinned and has an appropriate level of conservatism in all stages.

In the following sub-sections, the revised methodology, which has 4 stages, is presented. For each stage in the revised methodology, a comparison to the corresponding step in the previous methodology [5] is made. It is noted that Step 3 of the former methodology is no longer required, as noted in Table 2.

3.2 Stage 1

In Stage 1, a "baseline" wasteform RF[2] is chosen. This is the wasteform RF for a 9 m drop of a DCIC containing loose waste, assumed to be powder. The wasteform RF is the fraction of sub-10 micron particulates that are available for release. The requirement for the baseline wasteform RF is to provide a value that is bounding for all the wastes that are placed inside DCICs, also considering that mixed types of waste will be placed inside some DCICs.

In Step 1 of the previous methodology, a baseline wasteform RF of $2x10^{-3}$ was chosen, which was obtained from Section 4.2.2 of the CEC report [6]. This value is based on the bounding RF for sub-10 micron particulates obtained from drop tests of PFA powder in various containers (e.g. cardboard boxes, plastic bags, paint tins) from a drop height of 9 m. These drops are "confined", where the powder is inside a "container". The main comment made in the evaluation of Step 1 was that this value of baseline wasteform RF may not be conservative for all wastes because the underpinning was based on confined experimental drops. The containers (paint tins, etc) act as a barrier to release, reducing the RF. It would be more appropriate to use unconfined experimental drops.

In Stage 1 of the revised methodology, a new baseline wasteform RF is proposed. This is based on "unconfined" experimental drops using glass specimens, which better represents the physics of what proportion of sub-10 micron particulates that are available for release inside the DCIC cavity (i.e. the wasteform RF).

The references in Table 1 were reviewed to find relevant RF data. The findings are summarised in Table 3 and Table 4. From the available data, it can be seen that the RF for PFA powder consistently produces an RF that is 2 or 3 orders of magnitude higher than that for titanium dioxide powder. A baseline wasteform RF for revised Stage 1 has been chosen based on PFA powders because this is the more conservative of the two powders.

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[2] The terminology "wasteform RF" is used here because this is the standard terminology for the fraction of particulates that are generated and available for release inside the waste package after an impact. The waste placed inside DCICs will be un-encapsulated and could be different types of waste (i.e. mixed waste). The mixed waste will not be treated, apart from potentially drying the waste. Therefore the term "wasteform" in this context does not imply the waste has formed some kind of monolith or product.

The data for PFA (fly ash) powders from Table 3 is shown in Figure 1. The points for the RF for sub-10 micron particulates (triangular markers) show little difference in the RF for lower drop masses below 10 kg, but a decrease in the RF for the highest drop mass of 20 kg. The results were discussed in a paper [12], which states:

> "*for the fly ash powder, a decrease of release fraction for masses much larger than 1 kg is observed. This can be understood because with increasing mass, an increasing amount of powder is screened and is prevented from being suspended*."

Although the justification for why the RF reduces as the mass dropped increases due to screening is plausible, the data appears to show a fairly constant average RF of approximately $1x10^{-2}$ sub-10 micron particulates for drop masses under 10 kg (shown by the red dashed line in Figure 1). However, there is insufficient test data to be confident in this average RF value. Therefore, to ensure that the revised methodology is conservative, the highest measured RF value of $1.8x10^{-2}$ sub-10 micron particulates is recommended for Stage 1 (highlighted in red in Table 3).

This is a factor of 9 larger than the baseline wasteform RF of $2x10^{-3}$ that was suggested in the previous methodology [5]. It is acknowledged that the revised baseline wasteform RF is very conservative. It is based on a limited number of small-scale tests on PFA powder. Further test data is required to establish whether this is appropriate for other wastes, which will be considered in Task 3.

Table 3: Release fractions for PFA powder in "unconfined" glass flasks, drop height: h = 9 m (reproduced from Table 7.1 of [11])

Size fraction	Mass of PFA powder dropped [kg]				
	0.1	0.4	2	10	20
<4.5 µm	1.25E-03	7.71E-04	4.97E-03	1.90E-03	7.88E-04
<10 µm	9.22E-03	6.00E-03	1.80E-02	7.56E-03	2.18E-03
>10 µm	1.84E-02	1.82E-02	3.83E-02	1.76E-02	3.35E-03

Table 4: Release fractions for titanium dioxide powder in "unconfined" glass flasks, drop height: h = 9 m (reproduced from Table 7.3 of [11])

Size fraction	Mass of titanium dioxide powder dropped [kg]				
	0.1	0.4	2	10	20
<4.5 µm	-	-	6.83E-06	5.12E-06	6.14E-06
<10 µm	-	-	1.43E-05	1.11E-05	1.17E-05
>10 µm	-	-	2.63E-05	2.90E-05	2.95E-05

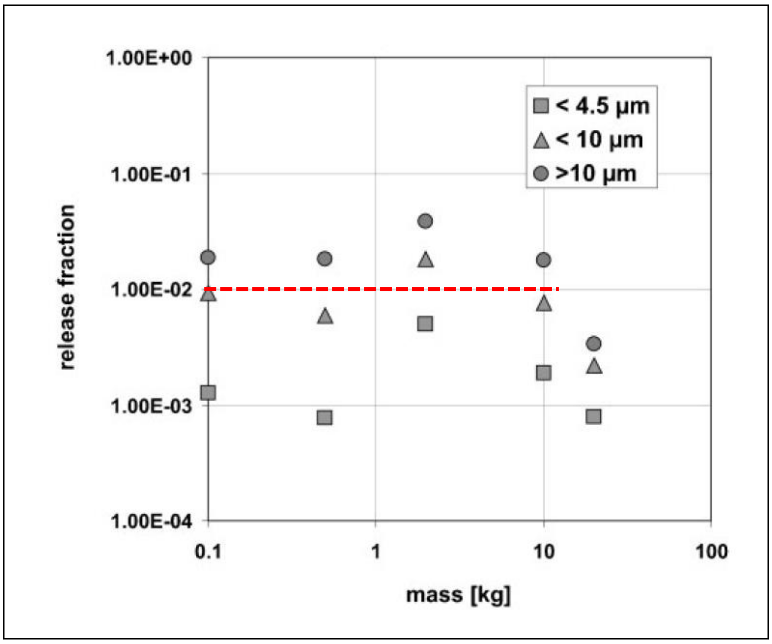

Figure 1: RF for differing masses of PFA in glass flasks for drop of 9 m (reproduced from Figure 12 of [12])

3.3 Stage 2

In Stage 2, the baseline wasteform RF from Stage 1 is scaled to account for different drop heights.

In the previous methodology, the "package" RF from small scale tests in the CEC report that was adopted as wasteform RF in Step 1 of the previous methodology was for a drop height of 9 m. Step 2 of the previous methodology applied a scale factor to scale the RF to different drop heights. The scale factor was calculated using an algorithm, based on powder spilled in air [6][10].

$$ARF = \frac{0.1064 \times M_0^{0.125} \times H^{2.37}}{\rho_{BP}^{1.02}}$$

Where ARF is the Airborne Release Fraction

M_0 is mass of powder spilled in kg

H is the spill height in m

ρ_{BP} is the bulk density of powder in kg/m^3.

In the previous methodology, to scale the wasteform RF from 9 m to 10.5 m, a scale factor of $(10.5/9)^{2.37}$ was applied to the wasteform RF from Step 1. The evaluation of this step in Task 1 [5] noted there is a significant difference in the mechanism for particulates to be airborne in a RS package during impact and the mechanism for powders spilled in air and the use of an algorithm based on powder spillage is not appropriate for scaling wasteform RF to height.

To update this step, existing experimental data was investigated. The variation of RF from the small-scale tests on powders in glass specimens are summarised in a technical paper [9].

Within this technical paper, experiments were performed on small glass containers, 200 litre drums and tin cans containing PFA or titanium oxide powders, which were dropped from various heights onto a flat target. The experiments on PFA inside glass containers (Figure 2) were considered to be “unconfined” because the glass shattered completely when dropped, allowing the particulates to be released into the test chamber. Section 4 of this paper states:

> “*Up to a drop height of 15 m, the release fraction grows almost linearly with the drop height*”.

It should be noted that only a limited number of experiments were carried out and therefore the validity of this linear relationship is uncertain.

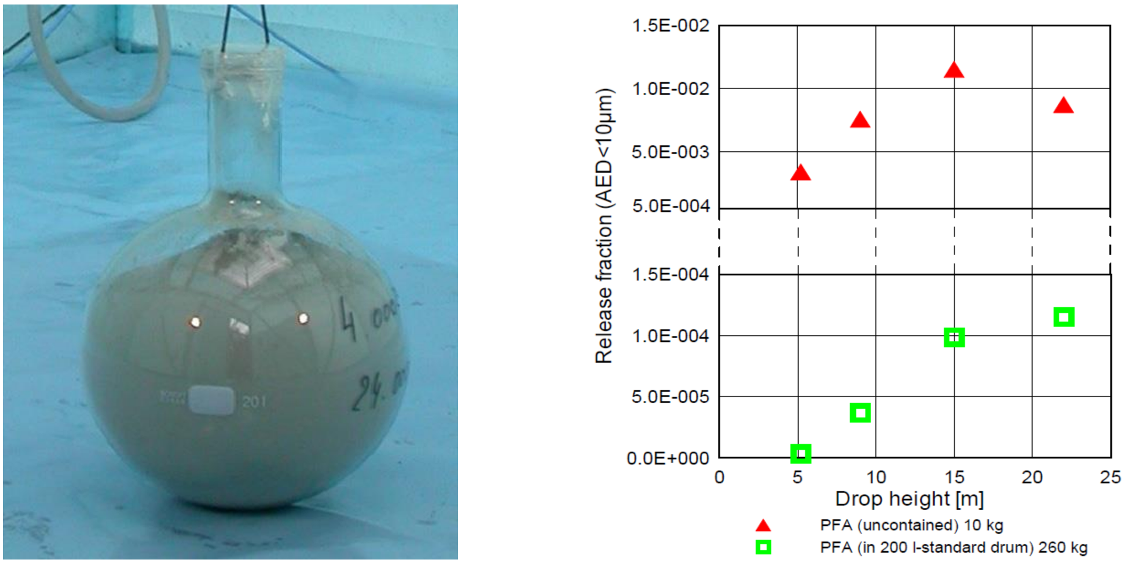

Figure 2: Experiments comparing RF for different drop heights from glass container containing PFA powder (from Fig 3.1 of [9]; results plot from Fig 4.3 of [9] – note the break in the ordinate (Y-axis), where the scale at the top and bottom of the plot are different)

The tabulated values of the experimental data were found in Section 7 of [14], containing further experimental details and these are reproduced in Table 5. The experimental data points corresponding to the red triangles in the graph shown in Figure 2 are highlighted in red in Table 5. Note that the first point at a drop height of 3.2 m was not included in Figure 2 of the technical paper [9].

Table 5: Summary of RF data from experiments for PFA experiments for mass = 10 kg for different drop heights (reproduced and translated from Table 7.4 of [11])

Size fraction	Drop height [m]				
	3.2	5.2	9	15	22
<4.5 µm	1.58E-04	9.99E-04	1.90E-03	4.00E-03	3.84E-03
<10 µm	6.94E-04	3.40E-03	7.56E-03	1.15E-02	8.71E-03
>10 µm	2.14E-03	6.23E-03	1.76E-02	2.19E-02	1.72E-02

Note: The experimental data points corresponding to the red triangles in the graph shown in Figure 2 are highlighted in red.

The same experiments on PFA in glass containers are described in a paper by the same authors, published in the Journal of Packaging, Transport, Storage & Security of Radioactive Materials [12].

> "*For a drop height of 22 m, a lower release fraction was measured. This may be related to the higher impact speed pushing the dust radially outwards against the walls of the control volume where part of the dust otherwise released into the airborne state is deposited.*"

The paper suggests for the drop height of 22 m, the result was erroneous, caused by the PFA particulates being deposited on the side walls of the experimental volume as the content was ejected outwards after the glass flask shattered instead of remaining airborne inside the experimental volume; in other words, the experimental volume was not large enough for this drop height. It is probably reasonable to discount this data point as an anomalous result.

Figure 3 shows the data in Table 2 for the sub-10 microns RF on a linear scale. The data for drop heights from 3.2, 5.2, 9 and 15 m are seen to display an approximately linear relationship. A line of "best-fit" was plotted using the Microsoft Excel linear regression calculation [15] for the first four drop heights. This best fit line has a regression parameter, R^2, of 0.98, which is close to 1, indicating a linear relationship is an appropriate approximation for this data-set for drop heights less than 15 m. However, as previously noted, only a limited number of experiments were carried out and therefore the validity of this linear relationship is uncertain.

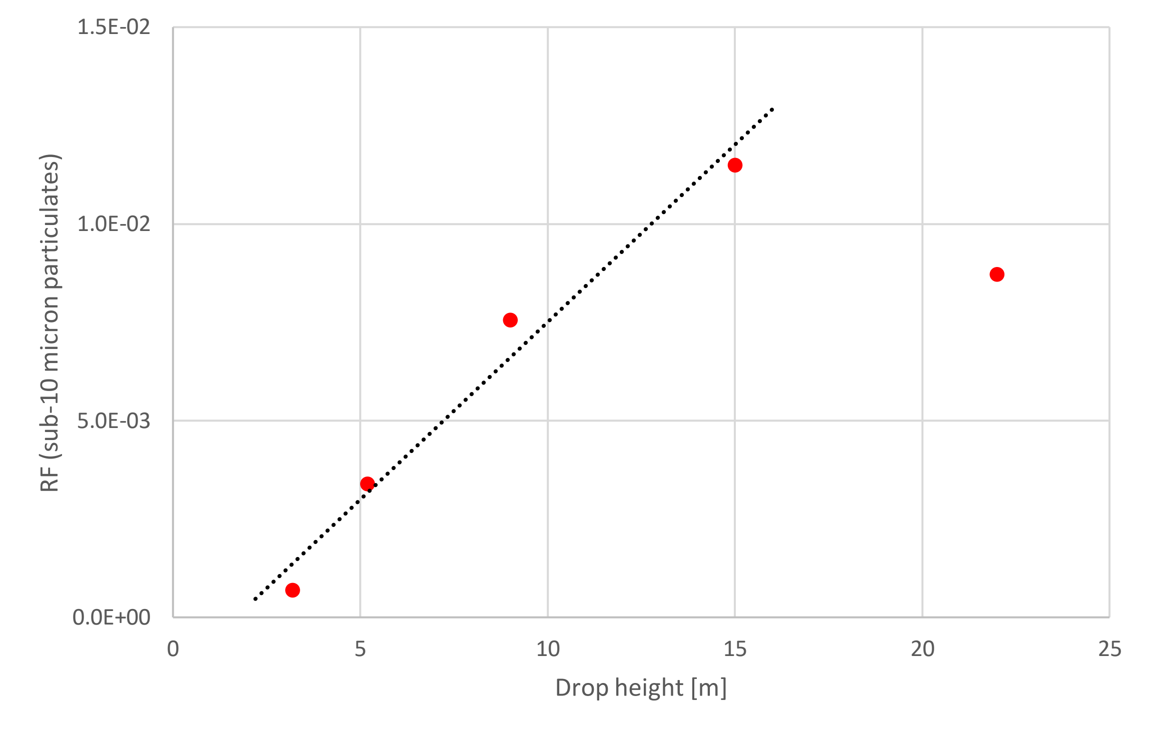

Figure 3: Glass container containing PFA powder used in experiments comparing RF from different drop heights (from data in Table 7.4 of [11])

For reference, an example of one of the experiments on glass containers is summarised in Table 6 and the shattered flask after the drop is shown in Figure 4.

Table 6: Example of experiment for drop of glass container from 9 m, from Section 10.2.1.1 of [11]).

Fall height	9 m
Container	10 l round-necked flask
Empty weight container	2000 g
Material	Fly ash - KM / C filler
Weight material	10 kg
Total weight	12 kg
Date / trial no.	14.07.2004 / No. 14

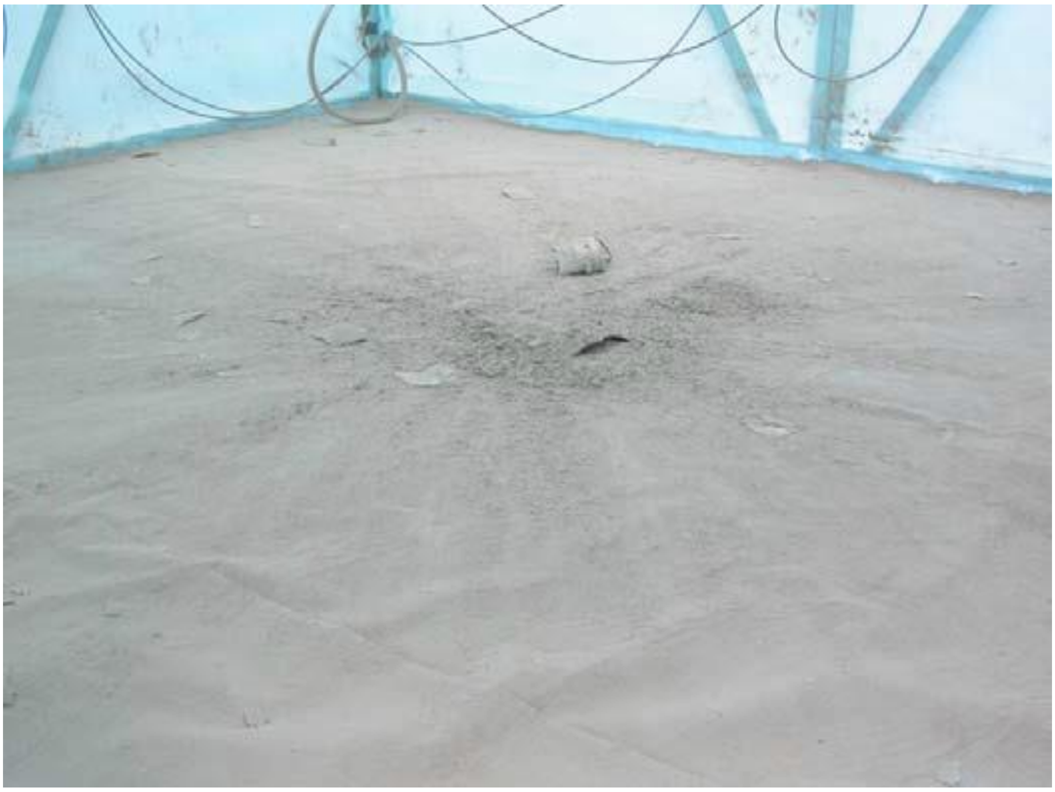

Figure 4: Experimental result for glass container containing 10 kg of PFA powder dropped from 9 m (from Section 10.2.1.1 of [11])

The data and results presented in the paper and the report have not described the experimental uncertainties. The experiments do not appear to have been repeated for each drop height. The uncertainty could be reduced with additional experimental data to verify the linear relationship of RF with drop height that has been proposed.

Although the experimental data [9][11][12] would benefit from verification by repeating some of the tests, the physics of the experiment better represents the actual mechanisms for scaling to height. The scaling in the updated Stage 2 is therefore a linear scaling with drop height, e.g. to scale from the baseline wasteform RF for a drop height of 9 m from Stage 1 to a drop height of 11 m, the baseline wasteform RF would be scaled by $^{11}/_{9}$ = 1.22.

3.4 Stage 3

Stage 3 scales the wasteform RF to take into account the type of wasteform inside the DCIC. This is done by considering the PSD of the waste.

This corresponds to Step 5 of the previous methodology, which took the DCIC_RF from Step 4 and multiplied it by the mass percentage of sub-100 micron particulates of the waste in the container. Since different wastes have differing PSDs, the scale factor applied in Step 5 should be based on the PSD of the specific waste that is proposed to be packaged inside the DCIC.

The main uncertainty with using the PSD for a particular waste is that it should represent the PSD of the waste after it has been impacted. The existing data in the references in Table 1 does not provide any additional scientific underpinning on the PSD for impacted wastes to determine how the PSD of un-impacted waste differs from the PSD for impacted waste. Therefore, some additional scientific underpinning would be useful.

However, assuming the waste is initially fully "broken up" before it is placed inside the DCIC (i.e. the waste contains the maximum proportion of sub-10 micron particulates for that type of waste), even if mechanical energy is applied to the waste during the impact, then the proportion of sub-10 micron particulates cannot increase compared to the fully broken up state.

Assuming the techniques used to measure the PSD of the waste gives a bounding proportion of sub-10 micron particulates, then this PSD could be used for Stage 3.

Stage 3 of the revised methodology is therefore to use the PSD of the waste, taken from measurement techniques that will lead to a bounding PSD of the impacted waste. If the PSD is not available, it should be assumed that 100 % of the waste consists of sub-10 micron particulates. It is acknowledged that whilst this assumption may be reasonable for powdered wastes, it is very conservative for other types of waste such as surface contaminated metals.

3.5 Stage 4

In the revised methodology, Stage 4 is the calculation of the package RF, corresponding to Step 4 in the previous methodology. The approach was based on assuming that the RS waste package is pressurised and, due to the impact, a loss of containment occurs around the lid/body interface as a result of permanent deformation. The amount of particulates released is assumed to vary with a linear relationship between internal and external pressure. The equation (below) is simple and is based on static equilibrium (i.e. equalisation of pressure) between inside and outside the waste container.

$$Package\ RF = Wasteform\ RF \times \frac{(internal\ absolute\ pressure - external\ absolute\ pressure)}{internal\ absolute\ pressure},$$

where the wasteform RF is calculated in Stage 3.

The main assumptions made by the previous methodology concerning the release of particulates include:

- There are no restrictions in the release pathway;
- The dynamics of the gas flow during the release are not significant;
- The mass ratio between the entrained sub-10 micron particulates and air is assumed to remain constant during the release;
- Only the airborne particulates are available for release;
- Ideal gas behaviour and isothermal conditions inside the container are assumed;
- A zero pressure gradient results in no release of particulates.

These assumptions are discussed below.

Restrictions in the release pathway

The previous methodology assumed an opening was present in/around the lid-body interface, but did not account for any blockage/holdup provided by restrictions in the release pathway or any clumping of particulates around the opening that may occur. Not taking these factors into account is a conservative assumption and this assumption is retained in the revised methodology.

Dynamics of the gas flow

The equation does not account for the dynamics of the gas flow during the pressure release. The rate of release through an opening will vary during an impact, depending on the opening orifice size, the orifice shape, how long it remains open and the instantaneous pressure difference. The existing data in the references in Table 1 do not provide any additional scientific underpinning regarding the physical processes involved in the pressure release.

To establish whether dynamic effects of the gas flow are significant, the following reasoning has been applied, based on our understanding of the physical mechanisms:

- During the impact, a lid-body gap opens up. The internal absolute pressure is greater than the external absolute pressure and the pressure difference causes the air inside the RSC cavity to be released to the outside;
- The velocity of the air flowing from the inside to the outside of the RSC is proportional to the square root of the pressure difference. At the start of the pressure equalisation, the pressure difference is at a maximum and the velocity of the air flowing out of the RSC cavity is at a maximum;
- As air escapes, the pressure inside the RSC decreases. Correspondingly, the velocity of the air escaping decreases, so that when the pressure gradient is close to zero, the air escaping has a relatively low velocity;
- Therefore, the dynamic effects of the pressure release are likely to be insignificant. The flow of air stops when the internal absolute pressure inside the RSC cavity has equalised to the external absolute pressure. The equation assumes the pressure equalisation is independent of time and that the internal gas volume will remain in thermal equilibrium with the container and its environment.

Mass ratio of particulates in air

The mass ratio between the entrained sub-10 micron particulates and air is assumed to remain constant during the release. This is a reasonable assumption as sub-10 micron particulates are assumed to be airborne. It is also reasonable to assume that the particulates entrained in the air inside the RSC cavity will flow with the air. Assuming the sub-10 micron particulates are uniformly dispersed within the air, when the pressure equalisation occurs, the proportion of air that escapes will be the same as the proportion of airborne particulates that escape.

Non-airborne particulates available for release

The previous methodology assumed that only the particulates that are airborne inside the RSC cavity are available for release. However, it is possible that some non-airborne wasteform may have collected at the opening in the containment or be very close to it. In this scenario, it is possible that some of the non-airborne particulates might be picked up by the flow of pressurised air and be expelled outwards through the opening. However, it is assumed that all of the sub-10 micron particulates will already be airborne inside the RSC cavity. In addition, the release pathway is assumed to be a tortuous route, so that very little of the non-airborne particulates would be able to escape the package. Therefore, the amount of sub-10 micron particulates released that were non-airborne inside the RSC is assumed to be very small. RWM have confirmed that a minimum gauge pressure of 0.5 bar will be assumed for all waste packages. If a release due to a pressure differential of at least 0.5 bar is assumed, then the potential release of non-airborne particulates through the opening would be insignificant, compared to the airborne particulates released, and can therefore be ignored.

Ideal gas behaviour and isothermal conditions

The equation assumes ideal gas behaviour and isothermal conditions inside the container. There is assumed to be no external heat input or cooling, so the internal volume does not heat up or cool down. Assuming that there is no cooling of the internal volume is a conservative assumption, as this will maximise the amount of air flow that is released and therefore the amount of particulates released.

Zero pressure gradient

For the case where the internal and external pressures are equal, the equation predicts that there is no release of particulates, i.e. a zero package RF. This is not conservative, because even with zero pressure difference, assuming there is an opening, some particulates might be expected to be expelled outwards as a result of their inertia or simply by diffusion. However, this inertial or diffusive release is expected to be very small in comparison to a pressure driven release. RWM have confirmed that a minimum gauge pressure of 0.5 bar will be assumed for all waste packages. If a release due to a pressure differential of at least 0.5 bar is assumed, then the potential inertial or diffusive release would be insignificant and can therefore be ignored.

Overall, given the above discussion of the main assumptions, the equation provides a conservative estimate of the amount of particulate that can be released. Therefore, the equation should be used for the revised methodology, with the assumption that a minimum internal gauge pressure of 0.5 bar is used.

3.6 Summary of Revised Methodology

A summary of the 4 stages of the revised methodology is presented in Table 7. A comparison of the stages in the revised methodology to the steps in the previous methodology is also provided. The revised methodology will produce higher package RFs than the previous methodology since it uses more appropriate scientific underpinning and is more conservative overall. These conservatisms could be reduced with further research and testing, which will be considered in Task 3.

Table 7: Summary of Revised Methodology

Revised Methodology Stage	Related Step in Previous Methodology	Purpose of Stage	Summary of Revised Methodology
1	1	Baseline wasteform RF	A baseline wasteform RF is proposed, which is the wasteform RF for sub-10 micron particulates for a drop height of 9 m. This was selected from experimental data from tests on "unconfined" glass specimens containing PFA powder. The baseline wasteform RF is 1.8×10^{-2}.
2	2	Scale to height	The baseline wasteform RF from Stage 1 is scaled linearly from a drop height of 9 m to the required drop height, e.g. for a drop height of 11 m, the scale factor would be $^{11}/_{9}$ = 1.22.
3	5	Scale wasteform RF by the mass percentage of sub-10 micron particulates in waste	This stage scales the wasteform RF by the mass percentage of sub-10 micron particulates obtained from measurements of the PSD of the waste. The PSD measurement techniques should be chosen to give a bounding PSD of the impacted waste. If the PSD is not available, it should be assumed that 100 % of the waste consists of sub-10 micron particulates and the scale factor should be assumed to be 1.
4	4	Relate wasteform RF to package RF	This stage relates the wasteform RF to the package RF. The release of particulates is assumed to be due to the flow of gas that has entrained particulates through an opening in the lid-body interface. This is based on the pressure difference between the inside and outside of the RS waste package. A minimum internal gauge pressure of 0.5 bar should be assumed for the calculation.

A worked example, comparing the previous and revised methodologies is provided in Appendix A.

3.7 Extension of revised RF methodology to a wider range of waste packages

The revised methodology is valid for the wastes that are expected to be packaged inside RSCs (see Table 1 of [5]). This section considers whether the revised methodology could be applied to a wider range of waste packages. To determine whether this is possible, the behaviour of the waste package in a drop from height, the nature of the contents, the method of release and the pathways for release for the specific waste package need to be considered.

Consideration must be given to both the waste container and the waste:

- The revised methodology assumes that the contents of the waste package are unencapsulated. If, for example, some of the waste is encapsulated, then the revised methodology will need to be modified;
- The revised methodology assumes that the behaviour of the container is "robust", specifically that it does not experience any significant change in internal volume or gross failure due to the impact. The revised methodology also assumes that a loss of containment occurs via a pressure driven release through an opening around the lid/body interface. To extend the methodology to other waste packages, the deformation to the waste package needs to be considered. This could be done by finite element analysis or experimental laboratory tests (scale-model or full-scale). If the deformation leads to gross failure in the container (e.g. tearing of the container skin, significant opening of the lid-body gap due to bolt failures, etc), then these additional release pathways need to be taken into account, as they may allow for more than just a pressure driven release. In addition, the deformation may cause a change in internal volume and an increase in the internal pressure.

An example of extending the RF methodology might be for unencapsulated (entombed) waste inside unshielded intermediate level waste (UILW) containers. Typically, UILW waste containers are not 'robust' and will deform in an impact accident, leading to a change in their internal volume. This will lead to an increase in internal pressure in the cavity and potentially increase the amount of particulates that are released through any openings. For UILW waste packages, there is also potential for a gross loss of containment, e.g. a large opening in the lid-body interface or a tear in the container skin. Particulates could be released through a mechanism that is not pressure driven e.g. ejection of material. Therefore, for UILW waste packages containing unencapsulated waste, a simple and conservative assumption could be that Stages 1, 2 and 3 of the revised methodology remain the same but in Stage 4, 100 % of the particulates available for release are assumed to be released.

There may also be potential to extend the revised RF methodology for other waste packages containing entombed waste, such as waste packages with a cementitious annulus. The overall RF for such waste packages will depend on whether the annulus is contaminated with radioactivity and the amount of deformation and size of the containment breach:

- For the case where the annulus is contaminated, the physical mechanism for the breakup and generation of particulates from the annulus is similar to an encapsulated waste. Therefore, for the calculation of particulates generated from the annulus, the holistic methodology for encapsulated wastes [16] would be more appropriate;

- If the containment is breached with a relatively small release pathway, then the release is likely to be a pressure driven release and the revised RF methodology could be used to calculate the proportion of particulates from the entombed waste that are released;
- If there is a relatively large containment breach, then particulates could be released through a mechanism that is not pressure driven e.g. ejection of material. In this scenario, a simple and conservative assumption could be that 100 % of the particulates available for release are assumed to be released.

Other types of waste package may contain a mix of encapsulated and entombed waste, e.g. where waste has corroded to form “pockets” of entombed waste that are surrounded by encapsulated wasteform or annulus. An example of this is uranium waste, which is encapsulated, but which has formed pockets of corroded product that are effectively entombed within the surrounding matrix. For such waste packages, the holistic methodology could be used for the encapsulated waste and the revised RF methodology for the entombed waste, with adjustments made to Stage 4 to take into how much particulate matter is released, based on the location of the entombed waste, whether the entombed waste is pressurised and the size of the breach waste container. In this scenario, it would be conservative to assume that all the particulates from the entombed waste that are available for release are released.

So, for the revised RF methodology to be extended to other waste packages, some modifications to the Stages of the revised methodology may be necessary. Table 8 provides a summary of the discussion of the validity of the revised RF methodology for a wider range of waste packages for each stage of the revised methodology.

Table 8: Considerations of revised RF methodology for applicability to a wider range of waste packages

Stage of revised methodology	Considerations for applicability to a wider range of waste packages
1: baseline RF	Stages 1, 2 and 3 are not dependent on the waste container but are dependent on the waste. These stages of the methodology are valid for unencapsulated waste (Note: encapsulated wasteforms have a different physical mechanism to generate particulates). Therefore, these stages could be applied to a wider range of waste packages containing unencapsulated waste.
2: scale to height	
3: use PSD of waste to scale based on proportion of sub-10 micron particulates	
4: release of particulates based on pressure gradient	Stage 4 assumes a pressure driven flow leading to particulate release through a lid-body gap. The RSC is assumed to be ‘robust’ with relatively low levels of deformation. For other waste packages, gross containment may not be retained and/or there could be a change in internal volume, leading to an increase in the pressure internally during the impact. In such cases, Stage 4 of the methodology requires some modification. A simple and conservative modification to extend the methodology to a wider range of waste packages might be to assume that 100 % of sub-10 micron particulates that are available for release are released; i.e. the wasteform RF equals the package RF.

4 Conclusions

A five step methodology to calculate the RF from DCIC was documented and reviewed in Task 1 [5] and the conclusion was that the underpinning for all the parts of the methodology may not be appropriate or contain appropriate conservatisms. This report presents Task 2, which was to update the methodology to ensure that each Stage has appropriate scientific underpinning. The revised methodology has 4 Stages:

- Stage 1: A baseline wasteform RF is proposed, which is the wasteform RF for sub-10 micron particulates for a drop height of 9 m. This was selected from experimental data from tests on "unconfined" glass specimens containing PFA powder. The baseline wasteform RF is 1.8×10^{-2}.
- Stage 2: The baseline wasteform RF from Stage 1 is scaled linearly from a drop height of 9 m to the required drop height, e.g. for a drop height of 11 m, the scale factor would be $^{11}/_{9}$ = 1.22.
- Stage 3: This stage scales the wasteform RF by the mass percentage of sub-10 micron particulates obtained from measurements of the PSD of the waste. The PSD measurement techniques should be chosen to give a bounding PSD of the impacted waste. If the PSD is not available, it should be assumed that 100 % of the waste consists of sub-10 micron particulates and the scale factor should be assumed to be 1.
- Stage 4: This stage relates the wasteform RF to the package RF. The release of particulates is assumed to be through an opening in the lid-body interface and is due to gas that has entrained particulates flowing through the opening. A minimum internal gauge pressure of 0.5 bar should be assumed for the calculation. The package RF is calculated using the equation:

$$Package\ RF = Wasteform\ RF \times \frac{(internal\ absolute\ pressure - external\ absolute\ pressure)}{internal\ absolute\ pressure}$$

The revised methodology is scientifically underpinned and is therefore recommended as a replacement to the previous methodology. It is recognised that the revised methodology will produce higher package RFs than the previous methodology as it is more conservative overall (see worked example in Appendix A). The conservatisms could be reduced with further research and testing, which will be considered further in Task 3.

There is good potential to extend the methodology to a wider range of waste packages containing unencapsulated waste, e.g. UILW packages containing entombed waste or a waste package that has corroded pockets of entombed waste inside an encapsulated waste matrix. Some modifications to Stage 4 would be necessary to account for differences in the amount of release from the waste package and this would be done on a case-by-case basis.

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Appendix A – Worked Example

In this hypothetical worked example, the waste is spent Ion Exchange (IEX) resin, which will be packaged into 500 litre RS drums. The PSD of the waste has been measured on the spent IEX resin, which showed the proportion of sub-10 micron particulates was 0.1 %. The techniques used for the PSD measurement are assumed to give a bounding value for the proportion of sub-10 micron particulates in the waste after the impact.

It is understood that the current requirements are for DCICs to be fitted with vents that will limit the internal pressure to 0.5 bar above atmospheric pressure. Therefore, the internal pressure of the DCIC has been assumed to be 1.5 bar absolute and the external pressure 1.0 bar absolute.

The worked example has used the GDF impact accident scenarios, which are a 10.5 m drop onto a flat unyielding target and a 9 m drop onto an aggressive target for the hypothetical example considered.

A.1 Previous Methodology

A worked example of the previous methodology is presented in this section. In this methodology, the sub-100 micron particulate size RF was calculated. There were 5 steps in the previous methodology, as described in Section 2. The main assumptions in the previous methodology are that gross integrity of the container is maintained and the release of particulates is via a flow of airborne particulates, caused by a pressure gradient, through a lid-body opening.

The current requirement is to calculate the RF for sub-10 micron sized particulates. (Previously, the requirement was to calculate the sub-100 micron RF.) Therefore, Step 3 of the previous methodology, in which a scale factor is applied to scale from sub-10 micron sized particulates to sub-100 micron sized particulates, is not required and has been omitted in the calculation here [14].

In Step 4, the internal pressure has been assumed to be 1.5 bar absolute and the external pressure 1.0 bar absolute. Using the equation in Section 2, the scale factor becomes: (1.5 – 1.0) / 1.5 = $^{1}/_{3}$.

For Step 5, the PSD of the waste is used to scale the package RF. For this example, PSD data on the spent IEX resin has been used, which showed the proportion of sub-10 micron particulates was 0.1 %.

The calculation of RF using the previous methodology is summarised in Table A.1. The values that change between the previous and revised methodologies are highlighted in red.

Table A.1: RF calculations for Spent Resin (previous RF methodology)

Parameter	Drop onto a flat, unyielding target	Drop onto an aggressive target
Package Type	500 litre RS drum	
Drop Height (m)	10.5	9
Step 1: sub-10 micron baseline RF	2 E-03	2 E-03
Step 2: height scale factor	1.44	1
Step 3: scale from sub-10 to sub-100 micron size	(omitted)	(omitted)
Step 4: proportion of particulates released due to pressure driven flow	$^{1}/_{3}$	$^{1}/_{3}$
Step 5: scale factor based on proportion of sub-10 micron particulates in resin	0.001	0.001
Sub-10 micron package RF	9.6 E-07	6.7 E-07

A.2 Revised Methodology

A worked example of the revised methodology is presented in this section. There are 4 stages in the revised methodology, as described in Section 3.6.

In Stage 1, the baseline RF is taken to be 1.8 E-02, based on a drop height of 9 m.

In Stage 2, the RF is assumed to scale linearly with height. For a drop height of 10.5 m, the scale factor is $^{10.5}/_{9}$ = 1.17.

In Stage 3, the proportion of sub-10 micron particulates is required for the impacted waste. As stated previously, the techniques used for the PSD measurement are assumed to give a bounding value for the proportion of sub-10 micron particulates in the waste after the impact. Therefore, the proportion of sub-10 micron particulates after impact is assumed to be 0.1 %.

In Stage 4, the internal pressure has been assumed to be 1.5 bar absolute and the external pressure 1 bar absolute. Using the equation in Section 3.5, the scale factor becomes (1.5 – 1) / 1.5 = $^{1}/_{3}$.

The calculation of RF using the revised methodology is summarised in Table A.2. In comparison to the RF from the previous methodology (see Table A.1), there is almost an order of magnitude increase in the RF. Again, the values that change between the previous and revised methodologies are highlighted in red.

Table A.2: RF calculations for Spent Resin (revised RF methodology)

Parameter	Drop onto a flat, unyielding target	Drop onto an aggressive target
Package Type	500 litre RS drum	
Drop Height (m)	10.5	9
Stage 1: sub-10 micron baseline RF	1.8 E-02	1.8 E-02
Stage 2: height scale factor	1.17	1
Stage 3: scale factor based on proportion of sub-10 micron particulates in impacted resin	$^{1}/_{3}$	$^{1}/_{3}$
Stage 4: proportion of particulates assumed released	0.001	0.001
Sub-10 micron package RF	7.0 E-06	6.0 E-06

ARUP Jacobs

Review and update of the impact performance methodology for Robust Shielded Intermediate Level Waste (RSILW) packages: Task 3 – Feasibility of a programme of research to further investigate RSILW package performance

S Shah

Jacobs Report Reference	208130/TR/003
Partner References	ARUP/247318-15
Client Name	Radioactive Waste Management Limited
Issue Number	Issue 3
Report Date	October 2021

DOCUMENT ISSUE RECORD

Document title	Review and update of the impact performance methodology for Robust Shielded Intermediate Level Waste (RSILW) packages: Task 3 – Feasibility of a programme of research to further investigate RSILW package performance
Project Reference	208130/TR/003

Issue	Description	Author	Checker	Approver	Approver	Date
Draft 1	For Jacobs comment	S. Shah (Arup)	C. Izatt D. Grant (Arup)	D. Gration (Arup)	-	Dec 2020
Draft 2	For RWM comment	S. Shah (Arup)	C. Izatt D. Grant (Arup)	D. Gration (Arup)	D. Lever (Jacobs)	Dec 2020
Issue 1	Addressing RWM comments	S. Shah (Arup)	C. Izatt (Arup)	D. Gration (Arup)	D. Lever (Jacobs)	Feb 2021
Issue 2	Addressing peer review comments	S. Shah (Arup)	C. Izatt (Arup)	D. Gration (Arup)	D. Lever (Jacobs)	Aug 2021
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ABSTRACT

A methodology for evaluating the Release Fractions (RFs) for Geological Disposal Facility (GDF) impact accident scenarios for Robust Shielded (RS) Intermediate Level Waste (ILW) Containers was provided to Arup by RWM. The methodology applies when gross structural integrity of the waste container is demonstrably maintained during an impact accident scenario. It has been used to form the basis of a Final Stage Letter of Compliance endorsement.

In Task 1, the methodology was documented and critically evaluated. It was recognised that the methodology was based on the information available at the time and that a pragmatic approach was employed where there were knowledge gaps. However, the conclusion to Task 1 was that some parts of the methodology were not appropriately underpinned or did not contain appropriate conservatisms. A revised RF methodology was presented in Task 2, which used existing data that had an appropriate level of scientific underpinning and conservatism.

This report presents the work done under Task 3, which is to propose and evaluate the feasibility of a programme of research to improve the scientific underpinning and reduce the conservatisms. Three proposals have been developed and are summarised as follows:

- To improve confidence in the baseline wasteform RF, small scale drop tests of different pulverised fly ash (PFA) powders in “unconfined” glass specimens from a drop height of 11 m are proposed;
- To improve confidence in scaling to height, small scale drop tests of PFA powder in “unconfined” glass specimens from various drop heights are proposed. These could be combined with the experimental programme to improve confidence in the baseline wasteform RF;
- The revised methodology from Task 2 assumes that the release of particulates is due to a pressure driven flow of airborne particulates through an opening in the lid-body gap and a minimum gauge pressure of 0.5 bar is used for the calculation of the release. The revised methodology assumes that any potential inertia driven release is very small compared to the pressure driven release. It is proposed to carry out analytical calculations to estimate the potential release due to an inertia driven mechanism. The work would be used to underpin the assumption that the inertia driven release is very small when compared to the pressure driven release and could subsequently be used to underpin a revised minimum pressure gradient requirement.

EXECUTIVE SUMMARY

A methodology for evaluating the Release Fractions (RFs) for Geological Disposal Facility (GDF) impact accident scenarios for Robust Shielded (RS) Intermediate Level Waste (ILW) Containers was provided to Arup by RWM. The methodology applies when gross structural integrity of the waste container is demonstrably maintained during an impact accident scenario. It has been used to form the basis of a Final Stage Letter of Compliance endorsement.

Radioactive Waste Management Ltd (RWM) commissioned Arup, as subcontractors to Jacobs (formerly Wood Nuclear), to investigate the scientific underpinning of the methodology. The objective of this work is to review, update and document the methodology for the determination of RFs from RSILW packages. The work has 3 tasks:

- Task 1: Documentation and evaluation of the methodology;
- Task 2: Update of the methodology;
- Task 3: Consider the feasibility of a programme of research to further investigate RSILW package performance.

Tasks 1 and 2 have been completed, with the methodology being evaluated and updated. This report presents the work done under Task 3. The scope involved:

- Reviewing each stage in the revised methodology developed in Task 2 and considering the uncertainties that remained;
- Evaluating the benefit of investigating these uncertainties, including the potential influence on the calculated RF and the feasibility of successfully completing the investigations;
- Providing an outline programme for future research.

Summaries of the future research proposals developed in Task 3 are given in the Table below.

#	Summary of Proposal	Objective of research programme	Possible effect on RF
1	Small scale drop tests of different pulverised fly ash (PFA) powders in “unconfined” glass specimens.	Improve confidence in baseline wasteform RF.	Potentially increase or decrease, but probably by less than one order of magnitude.
2	Small scale drop tests of PFA powder in “unconfined” glass specimens from various drop heights.	Improve confidence in scaling to height.	Potentially increase or decrease, but probably by less than one order of magnitude.
3	Analytical calculation to model one of the inertial release mechanisms of particulates for scenario with zero pressure difference.	The work would be used to underpin the assumption that the inertia driven release is very small when compared to the pressure driven release and could subsequently be used to underpin a revised minimum pressure gradient requirement.	Expected to have no effect on package RF. The work could subsequently be used to underpin a revised minimum pressure gradient.

CONTENTS

FIGURES AND TABLES

Glossary

Acronym	Definition
AED	Aerodynamic Equivalent Diameter
BEIS	Department for Business, Energy and Industrial Strategy
CEC	Commission of the European Communities
DCIC(s)	Ductile Cast-Iron Container(s)
DSS	Disposal System Specification
DUO	Depleted Uranium Oxide
GDF	Geological Disposal Facility
GNS	Gesellschaft für Nuklear-Service mbH
LSA	Low Specific Activity
ILW	Intermediate Level Waste
NDA	Nuclear Decommissioning Authority
NUREG	(United States) Nuclear Regulatory Commission (Report)
PFA	Pulverised Fly Ash (note that in other documents PFA is also used as an abbreviation for Pulverised Fuel Ash)
PSD	Particulate Size Distribution
PSSR	Pressure Systems Safety Regulations
RF	Release Fraction
RS	Robust Shielded
RSC	Robust Shielded Container
RSILW	Robust Shielded Intermediate Level Waste
RWM (formerly RWMD)	Radioactive Waste Management Limited (formerly Radioactive Waste Management Directorate)
TiO_2	Titanium dioxide
WAC	Waste Acceptance Criteria

1 Introduction

1.1 Background

The Nuclear Decommissioning Authority (NDA), through Radioactive Waste Management (RWM), is responsible for implementing UK Government policy for long-term management of higher activity radioactive wastes. Government policy for geological disposal of higher activity radioactive wastes, preceded by safe and secure interim storage, is set out in a policy paper by the Department for Business, Energy and Industrial Strategy (BEIS) [1].

As the implementer and future operator of a Geological Disposal Facility (GDF), and therefore as the ultimate receiver of the waste for disposal, RWM will be responsible for the production of waste acceptance criteria (WAC) for the facility. While plans for the construction of a GDF remain at an early stage the information necessary to define WAC is not available. In the meantime, and as a precursor to the WAC, RWM produces packaging specifications and assesses packaging proposals from waste packagers with the aim of minimising the risk that conditioning and packaging of wastes will result in waste packages that are incompatible with the GDF. This is called the Disposability Assessment process.

The Disposability Assessment process typically follows a staged approach, based on an idealised packaging development project. The typical stages of the Disposability Assessment process are as follows:

- Conceptual stage – establish whether, in principle, the waste package is likely to be compliant with RWM requirements;
- Interim stage – establish whether the evidence allows demonstration that the as-designed waste packages are compliant with RWM requirements; and
- Final stage – determine whether the evidence demonstrates that the as manufactured waste packages would be compliant with RWM requirements.

Evidence to scientifically underpin the performance of these waste packages is required in order for the waste packages to be favourably assessed. At each stage, evaluations are performed in several technical areas in order to assess compatibility with the waste packaging specifications. One of these areas is the performance of the waste package during an impact accident scenario. Evaluating packages in this area requires the determination of a Release Fraction (RF) for the package, in order to determine the bounding releases expected in an impact accident scenario.

The concept of Robust Shielded (RS) waste packages is that the container is intended to provide the required performance, without having to rely on the properties of the wasteform. The Ductile Cast-Iron Containers (DCICs) proposed for use by Magnox are examples of RS waste containers. Two variants of RS containers (RSCs) currently have waste packaging specifications, these are:

- 500 litre robust shielded drum [2];
- 3 cubic metre robust shielded box [2].

RWM has accepted changes to the generic Disposal System Specification (DSS) [3] to include 500 litre robust shielded drum packages based on the Gesellschaft für Nuklear-Service mbH (GNS) MOSAIK Type II container and 3 cubic metre robust shielded box based on the GNS Type VI container with the condition that the waste packages must be vented. Due to the possibility of corrosion and gas production within the waste, DCICs are expected to maintain a higher pressure than the outside environment, and the principal performance requirement of the vent is to keep this internal pressure below 0.5 bar gauge. As such, following an impact accident, there may be a pressure driven release of radioactive particulates from the DCICs if the seals fail. (Note that the DCICs may have vents and filters present, but these are not the assumed release path. The purpose of the filters is to prevent the gauge pressure inside the DCIC from exceeding 0.5 bar to ensure that the DCICs are not classed as pressure vessels under the Pressure Systems Safety Regulations (PSSR) [4]).

A methodology to derive RFs of RS waste packages in GDF impact accident scenarios has been provided to Arup by RWM. The methodology has been adopted by a waste producer to derive the RF of their RS waste package.

RWM commissioned Arup, as subcontractors to Jacobs (formerly Wood Nuclear), to review, update, and document this methodology. The work was organised into three tasks:

- Task 1: Documentation and evaluation of the methodology;
- Task 2: Update of the methodology;
- Task 3: Consider the feasibility of a programme of research to further investigate RS waste package performance.

The methodology was documented and evaluated in Task 1 [5]. It was recognised that the methodology was based on the information available at the time and that a pragmatic approach was employed where there were knowledge gaps. However, the conclusion to Task 1 was that some parts of the methodology were not appropriately underpinned or did not contain appropriate conservatisms. In Task 2 [6], using existing data, the methodology was revised to have an appropriate level of scientific underpinning and conservatism.

1.2 Objective and Scope

The objective of Task 3 was to consider the feasibility of a programme of research to further investigate RS waste package performance.

The scope of work for Task 3 was to:

- Review each stage in the revised methodology developed in Task 2 [6] and consider the uncertainties that remain.
- Evaluate the benefit of investigating these uncertainties, including the potential influence on the calculated RF and the feasibility of successfully completing the investigations.
- Provide an outline programme for future research.

2 Summary of Revised RF Methodology

A revised RF methodology, which has 4 stages, was developed in Task 2 [6]. A summary of the steps and the evaluation from the Task 2 report is given in Table 1.

Table 1: Summary of the stages in the revised RF methodology

Revised Methodology Stage	Purpose of Stage	Summary of Revised Methodology
1	Baseline wasteform RF	A baseline wasteform RF is used, which is the wasteform RF for sub-10 micron particulates for a drop height of 9 m. This was selected from experimental data from tests on “unconfined” glass specimens containing pulverised fly ash (PFA) cement powder. The baseline wasteform RF is 1.8×10^{-2}.
2	Scale to height	The baseline wasteform RF from Stage 1 is scaled linearly from a drop height of 9 m to the required drop height, e.g. for a drop height of 11 m, the scale factor would be $^{11}/_{9}$ = 1.22.
3	Scale wasteform RF by the mass percentage of sub-10 micron particulates in waste	This stage scales the wasteform RF by the mass percentage of sub-10 micron particulates obtained from measurements of the particulate size distribution (PSD) of the waste. The PSD measurement techniques should be chosen to give a bounding PSD of the impacted waste. If the PSD is not available, it should be assumed that 100 % of the waste consists of sub-10 micron particulates and the scale factor should be assumed to be 1.
4	Relate wasteform RF to package RF	This stage relates the wasteform RF to the package RF. The release of particulates is assumed to be due to the flow of gas that has entrained particulates through an opening in the lid-body interface. This is based on the pressure difference between the inside and outside of the RS waste package. A minimum internal gauge pressure of 0.5 bar should be assumed for the calculation.

3 Review of Stages in Revised Methodology

The revised methodology, presented in Task 2 [6] and summarised in Table 1, is scientifically underpinned. It was recommended as a replacement to the previous methodology evaluated in Task 1 [5]. It is recognised that the revised methodology will produce higher package RFs than the previous methodology as it is more conservative overall. The conclusions from Task 2 were that some of the conservatisms could be reduced with further research and testing and some of the scientific underpinning would benefit from additional data to improve the confidence in the numerical values used.

In Stage 1, a baseline wasteform RF was produced, based on a drop height of 9 m. The baseline wasteform RF was based on the maximum value from a small number of experiments that were performed on small scale "unconfined" glass specimens containing pulverised fly ash (PFA) cement powder, as shown in Section 4.3.2. The revised RF methodology would benefit from an improvement in the confidence of this value by performing repeat experiments. This is discussed further in Section 4.

In Stage 2, a linear scale factor is applied for different drop heights. This was based on a limited number of experiments on "unconfined" glass specimens containing PFA powder. A single experiment was performed at each drop height. The revised RF methodology would benefit from an improvement in the confidence of the experimental values used to derive the linear assumption by performing repeat experiments. This is discussed further in Section 5.

In Stage 3, the proportion of sub-10 micron particulates is obtained from the PSD of the waste. As discussed in the Task 2 report [6], as long as the PSD measurement leads to a bounding proportion of sub-10 micron particulates, further research is not necessary for Stage 3.

In Stage 4, an equation is used to determine the package RF, by assuming a pressure driven flow due to equalisation of the internal and external pressure of the RS waste package. Using the equation in Stage 4 when there is zero pressure difference leads to a prediction of a package RF of zero. This is not conservative, because even with zero pressure difference, assuming there is an opening, some particulates might be expected to be expelled outwards as a result of inertia. However, this inertial release is expected to be very small in comparison to a pressure driven release. RWM has confirmed that a minimum gauge pressure of 0.5 bar will be assumed for all waste packages. If a release due to a pressure differential of at least 0.5 bar is used, then the potential inertial release has been assumed to be insignificant and could be ignored. This assumption would benefit from further scientific underpinning, as discussed in Section 6.

The proposed investigations are described in the following sections.

4 Experimental Programme to Improve Confidence of Baseline Wasteform RF in Stage 1

A baseline wasteform RF[1], which is the fraction of particulate that is airborne and available for release inside the cavity of the RSC, was proposed in Stage 1 of the revised methodology, based on tests on "unconfined" glass specimens containing PFA powder that were dropped from 9 m into an experimental volume, as shown in Section 4.3.2. The amount of particulate that was airborne after the drop was measured. The baseline wasteform RF in Stage 1 was based on the maximum value from a small number of experiments. The revised RF methodology would benefit from an improvement in the confidence of this value by performing repeat experiments.

There are two main parameters in the proposed experimental programme:

1. Type of powder used in experiments, discussed in Section 4.1;
2. Number of experiments performed, discussed in Section 4.2.

The outline experimental programme is described in Section 4.3.

4.1 Type of Powder used in Experimental Programme

The baseline wasteform RF in the revised methodology [6] is the sub-10 micron particulate size wasteform RF and was based on experiments performed on PFA powder in glass specimens. These glass specimens were "unconfined" because they shattered on impact, so there is effectively no barrier to the powder being released. The programme of work was undertaken by the Commission of the European Communities (CEC) and included a smaller set of separate experiments using titanium dioxide powder [7].

Research in [8] looked at the PSD of various forms of wastes and appropriate powder simulants. This led to the following conclusions (from Section 4 [8], where LSA is Low Specific Activity):

> "*In summary, the following surrogate materials* (i.e. simulants) *are for the experiments to be carried out considered suitable and representative of various dispersible LSA materials:*
>
> *- Quartz flour as a surrogate for ash, concrete dust or diatomaceous earth*

[1] The terminology "wasteform RF" is used here because this is the standard terminology for the fraction of particulates that are generated and available for release inside the waste package after an impact. The waste placed inside RS waste packages will be un-encapsulated and could be different types of waste (i.e. mixed waste). The mixed waste will not be treated, apart from potentially drying the waste. Therefore, the term "wasteform" in this context does not imply the waste has formed some kind of monolith or product.

- Quartz powder mixed with quartz sand for U_3O_8 and powdered resin

- Fly ash (PFA) or house ash as a surrogate for radioactive ash

- Slag sand for ash, concrete dust or fines

- Titanium dioxide for uranium dioxide"

The size distribution of a number of different powders, including PFA powder, is shown in Figure 1 [9]. The majority of the particulates in PFA powder were sub-100 micron in size and approximately one third of the particulates were sub-10 micron in size. For titanium dioxide powder, the particle size distribution is shown in Figure 2, where it can be seen that more than 95 % of the particulates are sub-10 micron in size [10].

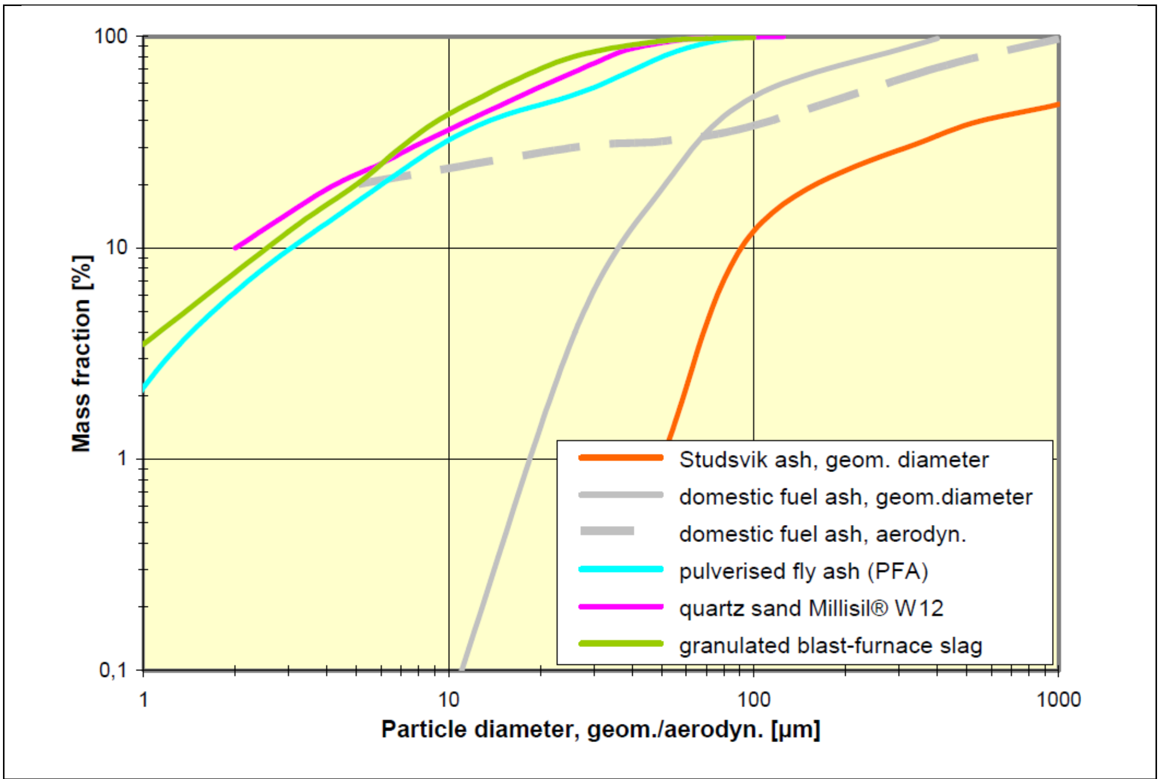

Figure 1: Particle size distribution of different powders[2] [9]

[2] geom. - geometric diameter; aerodyn. - aerodynamic equivalent diameter, as described in Reference [9]

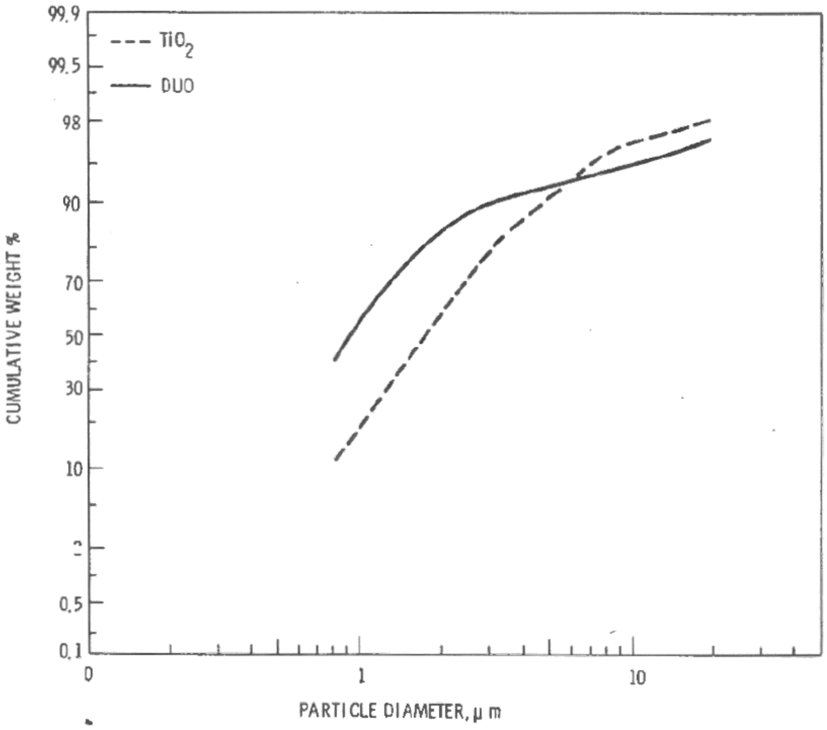

Figure 2: Particle size distribution of titanium dioxide (TiO_2) and depleted uranium oxide (DUO) powders [10]

The baseline wasteform RF is for sub-10 micron particulates. It might be assumed that powders where the majority of particulates are sub-10 micron in size would lead to a higher sub-10 micron RF, the goal being to lead to a conservative baseline wasteform RF. However, the evidence presented in [9] show that this is not necessarily the case. Experiments have been performed on PFA powder and titanium dioxide (TiO_2) powder. The technical paper [9] states (where AED is Aerodynamic Equivalent Diameter):

> "*Drop experiments applying medium and real sized specimens of different dispersible material (pulverised fly ash and TiO_2) have shown that the release behaviour of dispersible powders strongly depends upon material properties, e.g. particle size distribution and cohesion forces. The very fine-grained TiO_2 powder (AED ≤ 1 μm) tends to form agglomerates which in turn give rise to an effectively reduced airborne release of the respirable particle fraction (AED < 10 μm). On the contrary, pulverised fly ash (PFA) with a broad particle size distribution (1 μm < AED < 100 μm) showed much higher dispersion propensity and a clearly higher release fraction due to smaller cohesion forces. The highest experimentally determined release fraction of respirable mass (AED < 10 μm) was obtained for uncontained fly ash…*"

Later in the paper [9], further explanation is given about the "dustiness" of the powder:

> "*The majority of the experiments was carried out using a type of pulverised fly ash (PFA) with a broad particle size distribution between 1 and 100 μm (AED) and a*

> *high dispersion propensity characterised as "dustiness". The size distribution and dispersion propensity of the PFA used can be considered as being representative for ash-type LSA[3] waste and to be conservative for most other powdery LSA-II materials*."

The conclusion from [9] is that the size distribution and dispersion propensity of the PFA powder is appropriate to represent that of the waste that will be placed inside RSCs. In addition, although titanium dioxide powder contains a significantly higher proportion of sub-10 micron particulates than PFA powder, PFA powder has a higher propensity to disperse. Overall, the use of PFA powder to represent powdered waste will be conservative in terms of the sub-10 micron baseline wasteform RF. For this reason, it is proposed that future experiments are performed using PFA powders.

The PSD and the propensity of PFA powder to disperse may vary depending on different types or sources of the PFA powder. As part of the experimental programme to improve confidence in the baseline wasteform RF, different PFA powders could be drop tested and the powder giving the highest wasteform RF could be used to give a conservative baseline wasteform RF.

4.2 Number of Repeat Experiments

The data and results for the experiments presented in [9] have not described the experimental uncertainties. The experiments do not appear to have been repeated for any of the drop heights or powder masses and the baseline wasteform RF in the revised methodology is based on the maximum value from a small number of experimental values [6]. The baseline wasteform RF would benefit from repeat tests to improve the degree of confidence in the value adopted.

Ideally, a high degree of confidence in experimental test results would be achieved by performing a large number of tests with the test results having a high degree of repeatability (i.e. a low amount of scatter). However, performing a large experimental programme is often prohibitive in terms of time and cost. Therefore, a compromise between the degree of confidence and the number of tests performed is needed. The relationship between the degree of confidence (i.e. the confidence level and the confidence interval) and the number of tests is discussed in Appendix A.

The minimum number of tests required to achieve a desired confidence level depends on both the standard deviation of the test results and the desired confidence interval. In general terms, a greater number of tests are necessary if:

- A higher confidence level is required;
- A lower confidence interval is required;
- The test results have a higher standard deviation.

It is difficult to accurately predict the number of tests that will be necessary to obtain a certain degree of confidence in the test results, because this depends on the mean and the standard deviation of the test results, both of which are unknown before the tests are

[3] The definition of LSA and LSA-II materials is given in SSR-6 [13].

performed. In order to determine the required number of repeat tests, some assumptions about the likely test results need to be made.

As discussed in Appendix A, based on a mean RF value $\bar{x}$ of 1.0 × 10^{-2}, a standard deviation of 2.0 × 10^{-3} and a confidence interval of 4.0 × 10^{-3}, then 9 repeat tests would achieve a degree of confidence equivalent to a 95 % probability that the mean RF value would be between $0.8 \times 10^{-2} \leq \bar{x} \leq 1.2 \times 10^{-2}$.

Therefore, it is suggested that, for the drop test programme, the minimum number of repeat tests performed for each drop configuration (i.e. PFA powder type, drop height, etc.) is nine. A larger number of repeat tests would be preferable and would lead to a higher degree of confidence in the test results, but it may be impracticable and/or unaffordable to perform large numbers of repeat tests.

4.3 Outline Experimental Programme

To improve confidence in the baseline wasteform RF, a repeat of the type of experiments performed by Martens et al [9] is proposed. It is expected that some specialist laboratory equipment would be required (e.g. for airborne particulate size distribution measurement).

The objective of the experimental programme is to improve the confidence in the baseline wasteform RF. At present, it is not clear whether the baseline wasteform RF will increase or decrease in value as a result of this experimental programme. It is also uncertain what the magnitude of the change in the baseline wasteform RF will be, but probably by less than one order of magnitude, based on the range of RFs observed in the existing experimental data and how accurately the RF has been measured.

The experimental programme will consist of 2 main tasks.

1. Measurement on PFA powder to determine PSD;
2. Small scale drop tests on PFA powder inside “unconfined” glass specimens and measurement of airborne RF using equipment inside experimental volume.

It is recommended that a “test specification” document is prepared and agreed with the testing facility during the planning and preparation of the experimental programme. This will detail the precise test set-up, laboratory equipment that will be used and procedures to ensure robust and repeatable measurements are taken.

RWM has suggested that the drop height for these tests for the baseline wasteform RF should be 11 m, rather than the 9 m used in the previous methodology [5]. This bounds the current maximum drop height in a GDF vault impact accident drop scenario for all existing waste package types.

In order to investigate the potential variation in the baseline wasteform RF generated by different types or sources of PFA powder, 3 different PFA powders could be tested to see what variation exists between different PFA powders.

4.3.1 Measurement on PFA powder to determine PSD

The first task is to measure the PSD of the 3 different PFA powders. Each sample of PFA powder should be dry and uncontaminated and ideally the same batch of powder should be used for all the drop tests of that particular type of PFA powder. Based on previous PSD measurements on PFA powders, the particulate size range is expected to be within 0.9 – 175 microns. Assuming the PFA powder is similar to previously measured values, the PSD measurements should be taken for the aforementioned range of sizes. In particular, the measurement should include the cumulative mass % below 1 micron, 10 microns and 100 microns. It would be beneficial to extend the measurements below 1 micron and above 100 microns in size to cover the full range of particulate sizes in PFA powder. This information may also be useful if the current particulate sizes of interest were to change at a future date.

4.3.2 Small scale drop tests on PFA powder inside "unconfined" glass specimens

For the proposed experimental programme, similar procedures and apparatus are required to those used by Martens et al [9]. A glass container is filled with PFA powder. It is dropped into an experimental volume. An example of an experimental volume is shown in Figure 5. The glass container shatters on impact and does not confine the powder. The powder disperses inside the experimental volume, with smaller particulates remaining airborne for a period of time. The size and mass of the airborne particulates are measured using specialist equipment. The measurement should be performed in a reasonable timescale, before the particulates settle, although it is noted that fine particulates settle relatively slowly.

The glass specimen containing PFA powder and the test volume used in the previous tests [9] are shown in Figure 3. The lifting and release mechanism are shown in Figure 4. Some photos showing an overview of the outside of the experimental volume are shown in Figure 5.

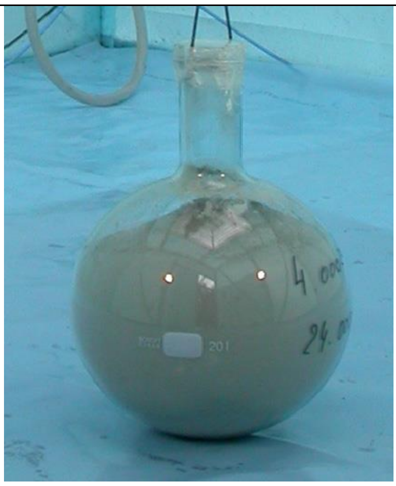	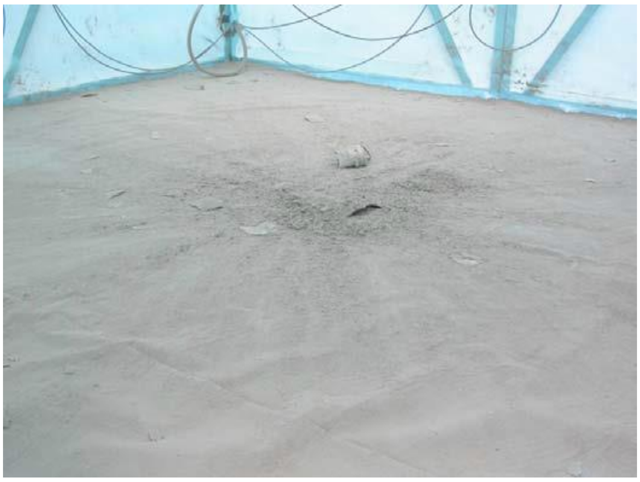
Glass container containing PFA powder, placed on floor before drop (floor is clear of all powder before drop)	Experimental result (after drop) for glass container containing 10 kg of PFA powder dropped from 9 m

Figure 3: Glass specimen containing PFA powder before and after drop [9]

Figure 4: Lifting and glass specimen release mechanism [8]

Figure 5: Experimental volume [12]

Reference [8] describes the experimental volume as having dimensions 4 × 4 × 3 m. After the drop, the powder has covered the entire floor area, as shown on the right-hand image in Figure 3, for a 10 kg powder mass and 9 m drop. The drop height proposed for the baseline wasteform RF measurement is 11 m, rather than 9 m, so a larger plan area will be required as the powder will be propelled further. There is a balance in how large the plan area should be. If it is too small, the powder will be propelled into the walls, where it will stick, rather than remain airborne, leading to a non-conservative RF measurement. If it is too large, the measurement of airborne particulate size and mass may take a long time as a greater volume of air has to be sampled. The exact dimensions should be agreed in the test specification, with a rough estimate being of the order of 5 × 5 × 3 m.

The ceiling has an opening to allow drop heights higher than 3 m. During the experiments, a procedure should be devised to immediately close the ceiling after the glass specimen has been dropped (e.g. with a sliding mechanism), whilst minimising disturbance of the airborne particulates that have been released inside the volume. A crane, hoist or "cherry picker" may be required to drop the specimens from the required height. The test could be set-up indoors or outdoors.

The RF for PFA powders from the CEC tests [8] is shown in Table 2 and the same data is presented in Figure 6. The current baseline wasteform RF of 1.8×10^{-2} is highlighted in red. The data for the RF for sub-10 micron particulates (triangular markers) show little difference in the RF for drop masses below 10 kg, but a decrease in the RF for the highest drop mass of 20 kg. The results were discussed in a paper [11] which states:

> "*for the fly ash powder, a decrease of release fraction for masses much larger than 1 kg is observed. This can be understood because with increasing mass, an increasing amount of powder is screened and is prevented from being suspended*."

Larger masses of powder could be prevented from being suspended in the experimental volume as the powder at the bottom is covered up by the powder above ("screened"), leading to a non-conservative measurement of the RF. Conversely, smaller masses may not be fully representative of the amount of waste placed inside RSCs. However, the apparent reduction in RF may not be real and may simply be the experimental scatter due to the lack of repeat measurements.

For the experimental programme, there are likely to be limitations on the experimental volume size and budget. The chosen mass of powder should aim to give a good balance between the required experimental volume and the conservatism in the measurement of RF. From the previous experimental work, summarised in Table 2, it can be seen that the 2 kg powder mass gave the highest sub-10 micron RF, although the experimental uncertainty in this value is unclear as it appears this was based on a single test. It is acknowledged that it is unlikely the RSC will contain just 2 kg of waste; however the purpose of the experimental programme is to calculate a baseline wasteform RF that is conservative for the range of wasteforms that will be placed inside RSCs. Another experimental consideration is the measurement of the airborne fraction. It may be the case that a higher mass, such as 10 kg or an intermediate value, could be selected if this leads to more accurate measurement of the RF in the experimental volume. The mass of powder to be used inside each glass specimen should be determined when the experimental programme is being developed, perhaps requiring some preliminary testing to fine tune the value.

Table 2: Release fractions for PFA powder in glass flasks, drop height: h = 9 m for particulate sizes <4.5 µm, <10 µm and >10 µm [8] (red text is experimental value giving the highest <10 µm RF)

Size fraction	RF of PFA release for a range of powder masses (mass in kg)				
	0.1	**0.4**	**2**	**10**	**20**
<4.5 µm	1.25E-03	7.71E-04	4.97E-03	1.90E-03	7.88E-04
<10 µm	9.22E-03	6.00E-03	1.80E-02	7.56E-03	2.18E-03
>10 µm	1.84E-02	1.82E-02	3.83E-02	1.76E-02	3.35E-03

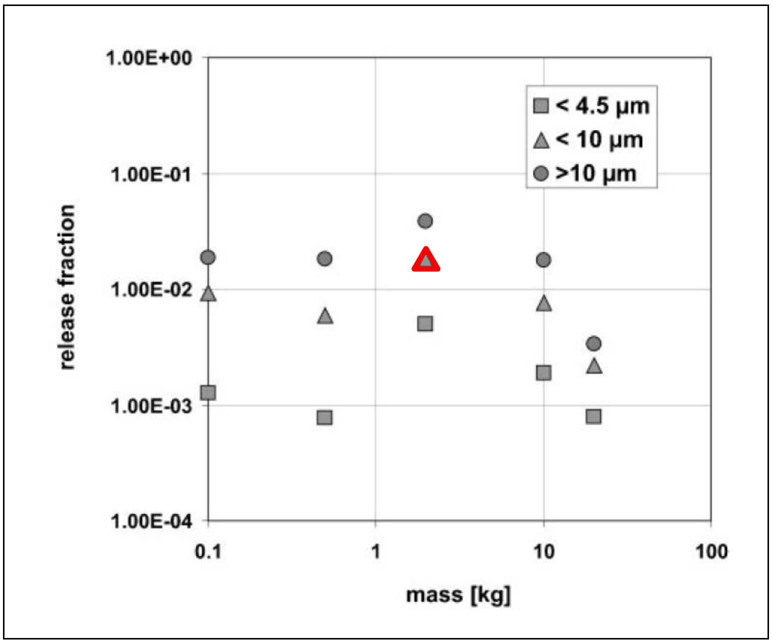

Figure 6: RF for differing masses of PFA in glass flasks for drop of 9 m for particulate sizes <4.5 µm, <10 µm and >10 µm [11] (red triangle is experimental value giving the highest <10 µm RF)

4.3.3 Measurement of airborne RF using equipment inside experimental volume

The report for the previous experiments [8] describes fans being used to homogenise the airborne powder after release. This will allow all of the suspended particulates to enter the particulate size measurement equipment. The fan speed should be set carefully, to avoid generating additional airborne particulates from settled powder but minimise the “loss” of any particulates. The experiment should be designed such that particulates that have already been measured are not “double-counted”, perhaps by collecting the measured particulates in a separate volume.

The particulate size was previously measured using a “Respicon” [12], a device that can simultaneously collect airborne particles in three size fractions (sub-100, sub-10 and sub-4 micron sizes). A similar such device could be used, which measures the total amount of sub-10 micron particulate that is airborne in the experimental volume after the impact.

4.4 Summary of Experimental Programme for Baseline RF in Stage 1

To improve confidence in the baseline wasteform RF, an experimental programme dropping PFA powder in “unconfined” glass specimens is proposed. A minimum of 9 drop tests from a drop height of 11 m on 3 different types of PFA powder (a total of at least 27 drop tests) is proposed to see what variation exists between different PFA powders. It is suggested that one set of experiments on one PFA powder is first undertaken to understand if nine repeats is enough, before moving onto other PFA powders. The experimental programme is essentially a repeat of one of the previous series of experiments [8] on glass specimens containing PFA powder. The experiment is therefore feasible and is similar in complexity to other recent small-scale drop tests that have been commissioned by RWM. Table 3 provides a summary of the main parameters of the experimental programme.

Table 3: Summary of main experimental parameters

Parameter	Description
Description of test	Small scale drop tests of PFA powder in “unconfined” glass specimens.
Objective of experimental programme	Improve confidence in baseline wasteform RF.
Tasks required	1. Measurement on PFA powders to determine PSD. 2. Small scale drop tests on PFA powders inside “unconfined” glass specimens and measurement of airborne RF using equipment inside experimental volume.
Powder	3 different “types” of PFA powder.
Drop height	11 m
Powder mass	A single mass, to be determined during experimental development
No. of tests	27 tests in total (9 tests per PFA powder)
Possible effect on wasteform RF	Reduce uncertainties; change in wasteform RF probably by less than one order of magnitude.

5 Experimental Programme to Improve Confidence of Scaling to Height in Stage 2

The variation of RF with drop height from the small-scale tests on powders in glass specimens is summarised in [9] and [11]. The same experiments described in Section 4 were performed, but at various drop heights. In Task 2 [6], a linear relationship was found between the drop height and RF, with the results summarised in Table 4 and shown in Figure 7. The linear relationship appears valid up to a drop height of 15 m, but it is acknowledged that the lack of repeat experiments leads to uncertainty in the derivation of a trend. However, the data point at 22 m appears not to fit the trend and appears to be anomalous, as noted in [11]:

> "*For drop heights <15 m, the release fraction increases linearly with drop height. For a drop height of 22 m, a lower release fraction was measured. This may be related to the higher impact speed pushing the dust radially outwards against the walls of the control volume where part of the dust otherwise released into the airborne state is deposited.*" [11]

Table 4: Summary of RF data from experiments for PFA experiments for mass = 10 kg for different drop heights [8]

Size fraction	Drop height [m]				
	3.2	5.2	9	15	22
<4.5 µm	1.58E-04	9.99E-04	1.90E-03	4.00E-03	3.84E-03
<10 µm	6.94E-04	3.40E-03	7.56E-03	1.15E-02	8.71E-03
>10 µm	2.14E-03	6.23E-03	1.76E-02	2.19E-02	1.72E-02

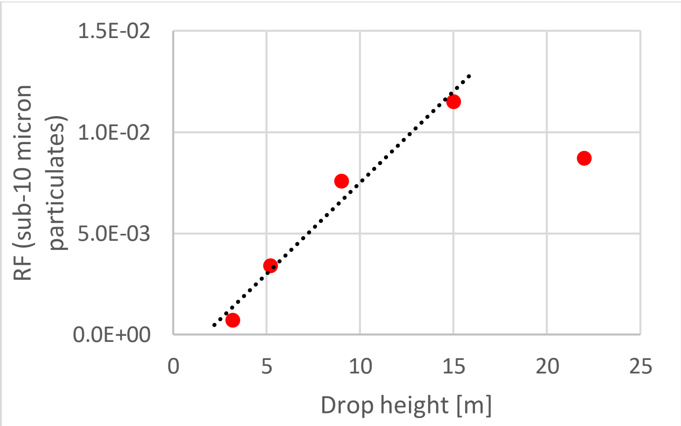

Figure 7: Glass container containing PFA powder used in experiments comparing RF from different drop heights [8]

The data and results presented in the paper [9] and the report [11] have not described the experimental uncertainties. The experiments do not appear to have been repeated for each drop height and therefore each point in Figure 7 represents only one experiment. The uncertainty due to this could be determined with additional experimental data to verify the linear relationship of RF with drop height that has been proposed in Task 2 [6].

After discussion with RWM, the following drop heights are proposed: 0.3 m, 7 m, 9 m and 11 m. It would be beneficial to combine this experimental programme with that in Section 4, as the experiment is very similar and the 11 m drop height results could be used for both studies.

The same experimental procedures as described in Section 4.3 should be used. The PFA powder that is used should be the powder that was determined to give the highest wasteform RF. For the drops from 11 m outlined in Section 4, it is suggested that the powder mass should be chosen to give a good balance between the required experimental volume and the conservatism in the measurement of wasteform RF. For consistency, it is recommended to use the same mass of powder for experiments from different drop heights.

It is possible that at the drop height of 0.3 m, the glass container may not shatter or may only partially break (i.e. the container may provide some containment to the powder) or the release will be too low to measure accurately. If this is the case, this drop height could be increased (e.g. to 1 m or higher).

As discussed in Section 4.2 and Appendix A, the minimum number of tests required to achieve a desired confidence level depends on both the standard deviation of the test results and the desired confidence interval. Therefore, similar to the drop test programme outlined in Section 4, it is suggested that the minimum number of repeat tests performed for each drop height is 9. A larger number of repeat tests would be preferable and would lead to a higher degree of confidence in the test results, but it may be impractical and/or unaffordable to perform large numbers of repeat tests. It is suggested that one set of experiments on one drop height is first undertaken to understand if nine repeats is enough, before moving on to different heights.

The experimental programme is essentially a repeat of previous experiments [8] on glass specimens containing PFA powder. The experimental programme is therefore feasible and is similar in complexity to other recent small-scale drop tests that have been commissioned by RWM. If the experiments are conducted jointly with the experiments on baseline wasteform RF described in Section 4, there is potential for cost savings, since similar experimental equipment and procedures are required. Table 5 provides a summary of the main parameters for the experimental programme.

Table 5: Summary of main experimental parameters

Parameter	Description
Description of test	Small scale drop tests of PFA powder in “unconfined” glass specimens from various drop heights
Objective of experimental programme	Improve confidence in scaling to height
Tasks required	1. Measurement on PFA powder to determine PSD. 2. Small scale drop tests on PFA powder inside “unconfined” glass specimens from various drop heights and measurement of airborne RF using equipment inside experimental volume.
Powder	PFA powder
Drop heights	0.3 m, 7 m, 9 m, 11 m
Powder mass	To be determined during experimental development
No. of tests	36 drop tests in total (Minimum 9 per drop height)
Possible effect on wasteform RF	Reduce uncertainties; change in wasteform RF probably by less than one order of magnitude.

6 Research to Improve Scientific Underpinning of Inertia Driven Releases in Stage 4

In Stage 4 of the revised methodology [6], the package RF is related to the wasteform RF by a scale factor which is calculated based on the static equalisation of pressure between the inside of the RSC cavity and the outside. The scale factor is calculated using the following equation:

$$Package\ RF = Wasteform\ RF\ x\ \frac{(internal\ absolute\ pressure - external\ absolute\ pressure)}{internal\ absolute\ pressure}$$

The scientific underpinning for this equation has been described in the Task 2 report [6]. The equation predicts zero release for the case where there is zero pressure difference (i.e. the internal absolute pressure equals the external absolute pressure). This may not be conservative as there exists an alternative physical mechanism for release – an inertial driven release. The inertial driven release would be in addition to the pressure driven release.

For the revised RF methodology [6], to avoid the scenario of a package RF of zero, a minimum pressure difference (the numerator in the above equation) of 0.5 bar will be used. This assumes that the inertial driven release would produce a significantly lower release than the pressure driven release (where the pressure difference is 0.5 bar) and could therefore be ignored. This assumption is qualitative and the methodology would benefit from research that would provide a quantitative value for the inertial driven release.

There are two mechanisms that could lead to an inertial driven release:

1) The first is the inertial driven flow of the waste (e.g. powder) that might force its way through any openings due to its own inertia as the waste package is decelerated during an impact;
2) The second inertial mechanism is that of the air inside the RSC cavity. During the impact, the inertia of the air will cause it to flow towards the target, generating a differential pressure at the opening of the RSC, causing air to flow through the opening.

For the first inertial mechanism, it is likely that any experiments that are devised to calculate this inertial driven release mechanism would be difficult to perform and likely involve full-scale model drop tests, which would be expensive and time-consuming. In addition, the release pathway is likely to be through a tortuous route via relatively small openings between the container body and lid, so the inertial driven release is likely to be very small. Therefore, experiments to investigate this inertial driven release are unlikely to be cost effective.

For the second inertial mechanism, an analytical hand calculation could be performed to calculate the approximate rise in the internal pressure due to the inertia of the air. It is expected that this would be significantly lower than 0.5 bar. This would provide scientific underpinning that the 0.5 bar minimum pressure gradient specified in the revised methodology is conservative for the case of zero pressure gradient. If the 0.5 bar minimum pressure gradient were to be reduced or removed at some time in the future, this calculation for the internal pressure due to an inertial driven release could be used to underpin a revised minimum pressure gradient requirement.

A summary of the main parameters to improve scientific underpinning of release in scenario of zero pressure difference is given in Table 6. The analytical calculation is a "desk study" and is expected to be relatively straightforward.

Table 6: Summary of main parameters for research to improve scientific underpinning of release in scenario of zero pressure difference

Parameter	Description
Description of research	Calculation of RF for scenario with zero pressure difference.
Objective of research programme	Provide scientific underpinning for one of the mechanisms of inertia driven flow. The work would be used to underpin the assumption that the inertial driven release is very small when compared to the pressure driven release and could subsequently be used to underpin a revised minimum pressure gradient requirement.
Tasks required	Analytical calculation.
Possible effect on RF	Expected to have no effect on package RF. The work could subsequently be used to underpin a revised minimum pressure gradient.

7 Conclusions

A revised RF methodology that had an appropriate level of scientific underpinning and conservatism, based on existing data, was presented in Task 2 [6]. The revised methodology would benefit from a programme of research to improve the scientific underpinning and reduce the conservatisms. In Task 3, proposals for this research have been developed and a summary of these proposals is given in Table 7.

Table 7: Summary of proposals for programme of research

#	Summary of Proposal	Objective of research programme	Possible effect on RF
1	Small scale drop tests of different PFA powders in "unconfined" glass specimens.	Improve confidence in baseline wasteform RF.	Potentially increase or decrease, but probably by less than one order of magnitude.
2	Small scale drop tests of PFA powder in "unconfined" glass specimens from various drop heights.	Improve confidence in scaling to height.	Potentially increase or decrease, but probably by less than one order of magnitude.
3	Analytical calculation to model one of the inertial release mechanisms of particulates for scenario with zero pressure difference.	The work would be used to underpin the assumption that the inertial driven release is very small when compared to the pressure driven release and could subsequently be used to underpin a revised minimum pressure gradient requirement.	Expected to have no effect on package RF. The work could subsequently be used to underpin a revised minimum pressure gradient.

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Appendix A – Number of Tests and Degree of Confidence

Ideally, a high degree of confidence in experimental test results would be achieved by performing a large number of tests with the test results having a high degree of repeatability (i.e. a low amount of scatter). However, performing a large experimental programme is often prohibitive in terms of cost and time. Generally, the fewer tests undertaken and/or the greater the amount of scatter means a lower degree of confidence in the results. This degree of confidence can be expressed using two values:

- A confidence interval, *L*, gives an estimated range of values which is likely to include an unknown population parameter (e.g. mean) with a probability, *γ*. The range of the confidence interval has a length, *L*. The estimated range is calculated from a given set of sample data (Section 25.3 of [14]);
- A confidence level, *γ*, which can be expressed as a percentage or fraction. The selection of a confidence level for an interval determines the probability that the confidence interval produced will contain the true parameter value (i.e. the true mean).

As an illustration, if, for a given set of test results, the mean value is 1.0×10^{-2}, the confidence interval is 0.4×10^{-2} and the confidence level is 95 %, then this implies that there is a 95 % probability that the mean value lies between 0.8×10^{-2} and 1.2×10^{-2}.

When planning a programme of tests, it is necessary to specify the number of repeat tests to be performed. However, it is difficult to accurately predict the number of tests, *n*, that will be necessary to obtain a certain degree of confidence. This is because the number of tests required to meet the desired confidence interval at the specified confidence level depends on the mean and the standard deviation of the test results, both of which are unknown before the tests are performed.

In general terms, as *n* increases, the mean and standard deviation are expected to converge to their “true” values. However, in practice, this would take a large number of tests, which is prohibitive. A more pragmatic approach is required, taking into account the cost of testing and perhaps accepting a lower confidence level, *γ*, and/or a wider confidence interval, *L*.

For the experimental programmes proposed in this work, the following variables can be defined (for a single mass of PFA powder and for each drop height):

- The number of tests is *n* (i.e. the number of glass specimens dropped is *n*);
- The mean value from these *n* tests is $\bar{x}$;
- The standard deviation of the test results is *s*;
- The confidence interval, *L*, is determined using a two-tailed t-distribution [14] and the number of degrees of freedom, *m*, which approximately equals *n* – 1.

There are several variables which are either set by the analyst (e.g. confidence level *γ*, confidence interval *L*, number of tests *n*) or unknown before the experiments (mean $\bar{x}$, standard deviation *s*).

The number of tests (sample size), n, required to achieve a particular confidence level, γ, and with a particular confidence interval, of length L, is approximately given by the following equation (from Section 25.3 of [14]):

$$n = \left(\frac{2\, t_{1-\gamma,m}\, s}{L}\right)^2$$

where $t_{1-\gamma,m}$ is the two-sided Student t statistic for confidence level, γ, and $m = n - 1$ degrees of freedom.

Since the t statistic is a function of n, the process of determining the required number of tests n to achieve the desired degree of confidence is iterative.

Using the above equation and various assumed values of s, L and γ, then the number of tests n can be calculated and some examples are provided in Table A.1.

Table A.1: Example of number of tests required

Confidence level, γ	Confidence interval, L	Standard deviation, s	Number of tests, n
80 %	2 E-3	5 E-3	42
	4 E-3	5 E-3	12
	4 E-3	2 E-3	4
90 %	2 E-3	5 E-3	70
	4 E-3	5 E-3	19
	4 E-3	2 E-3	6
95 %	2 E-3	5 E-3	98
	4 E-3	5 E-3	27
	4 E-3	2 E-3	9

It can be seen that the number of tests required rapidly increases for higher confidence levels, lower confidence intervals or higher standard deviations.

Based on the existing data for the 9 m drops for different powder masses (see Section 4.3.2 and Figure 6), the following values have been derived:

- The sample mean RF was about 1.0×10^{-2} (ignoring the 20 kg powder mass);
- The sample standard deviation was about 5.4×10^{-3}. It is acknowledged that this standard deviation is derived from 4 drop tests with different drop masses rather than 4 drop tests that were exactly the same test. However, this is the only test data available to be able to estimate the standard deviation.

Based on this standard deviation, and assuming that the mean RF from the proposed 11 m drop tests will have a similar mean value of 1.0×10^{-2}, then in order to achieve a confidence level of 95 % and a confidence interval of 4.0×10^{-3} (i.e. a 95 % probability that the mean RF value is between $0.8 \times 10^{-2} \leq \bar{x} \leq 1.2 \times 10^{-2}$), then approximately 27 repeat tests would be required. Alternatively:

- If the confidence level was reduced from 95 % to 80 %, then the number of repeat tests required would be 12;
- If the standard deviation of the test results could be reduced to 2.0×10^{-3}, then the number of repeat tests required would be 9.

As noted above, the standard deviation of 5.4×10^{-3} was derived from 4 drop tests performed using different masses of powder. It is thought likely that repeat drop tests using exactly the same experimental parameters should be able to achieve a lower amount of scatter and therefore a lower standard deviation. In addition, as more repeat tests are performed, the standard deviation of the test results should also reduce. Therefore, it is thought likely that a lower standard deviation could be achieved for the proposed drop test programmes.

Therefore, it is suggested that, for the drop test programmes discussed in this report, the minimum number of repeat tests performed for each drop configuration (i.e. PFA powder type, drop height) should be 9. A larger number of repeat tests would be preferable and would lead to a higher degree of confidence in the test results, but it may be impractical and/or provide poor cost benefit to perform large numbers of repeat tests.

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