Proceedings of the 18th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2016
September 18-23, 2016, Kobe, Japan

Paper No. 2036

Development of fissile package contents limits for intermediate level waste packages

Michael Hobson
Sellafield Limited

Iain Phimister
Radioactive Waste Management Limited

John Harvey
Radioactive Waste Management Limited

Steve Middleton
International Nuclear Services

Abstract

Radioactive Waste Management Ltd (RWM) is responsible for developing a geological disposal facility for the UK's higher activity waste. In support of this RWM develops and maintains a generic transport system design to demonstrate that radioactive waste packaged now will be safe to transport to a geological disposal facility in the future.

Some Intermediate Level Wastes planned for disposal at a geological disposal facility will require transport in a Type B(U/M)F package design owing to their fissile material content. Accordingly RWM has historically defined safe fissile masses for a range of package designs. Diversity in waste composition has been allowed for by grouping wastes into bands and defining a safe fissile mass for each band. For instance bands covering a range of isotopic composition e.g. irradiated natural/slightly enriched uranium, low enriched uranium, etc. On the other hand uncertainty in the disposition of material within a package has been allowed for by pessimistically assuming the material forms an optimal configuration. This pessimistic assumption has led to the definition of very restrictive safe fissile masses.

RWM working together with International Nuclear Services and Sellafield Ltd has developed an approach to grouping wastes by material distribution in order to reduce the pessimism in the safe fissile masses. Material distribution bands have been defined for a worst-case of unlimited non-uniformity (corresponding to the historical limits for an optimal configuration) and for material distributions that allow credit to be taken for a known degree of mixing. The approach is supported by compliance rules to enable wastes to be assigned to an appropriate distribution band. This paper describes the approach to defining less restrictive safe fissile masses.

Introduction

RWM working together with International Nuclear Services and Sellafield Ltd has developed a new approach to the transport criticality safety assessment for the latest SWTC (Solid Waste Transport Container) family of transport containers.

The preliminary application of the new approach has resulted in less restrictive safe fissile masses. However it has also resulted in a need to undertake a very large number of calculations to ensure that for all parameters where the value is unknown, the calculation has applied the value that maximises neutron multiplication.

This paper suggests that there is a need for a modified approach that provides an appropriate balance between the assessment of all possible permutations of all unknown parameter values and the assurance that the modelled system bounds any credible package.

Background

RWM has developed a range of transport container designs in order to provide confidence that radioactive wastes packaged now will be suitable for transport to a Geological Disposal Facility in the future. Those transport container designs underpin the assessment of the transport safety of waste packaging proposals through the Letter of Compliance Disposability Assessment process.

The SWTC family of transport containers are cuboidal steel containers with 70 mm 150 mm or 285 mm of steel shielding and are designed to transport either four 500 litre drums in a stillage, one 3 cubic metre box, one 3 cubic metre drum or one Miscellaneous Beta Gamma Waste Store box, as a Type B(M)F transport package (see Figure 1 for an illustration of an SWTC).

The SWTC family was developed to replace the earlier RSTC (Reusable Shielded Transport Container) family of designs. Most notably the SWTC design was developed to incorporate a simplified lid closure mechanism using a bolted arrangement and to reduce the cavity corner radius in order to accommodate waste packages that did not have rounded corners.

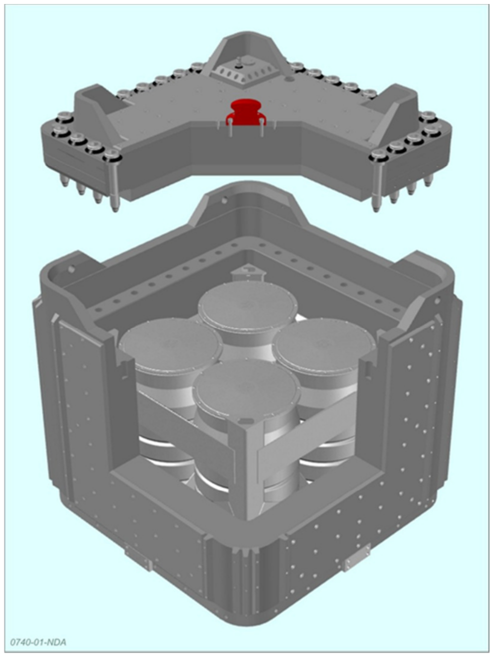

Figure 1 Cut-away drawing of SWTC-285 containing a stillage of four 500 litre drums

A Design Safety Report Part III for the RSTC [1] has previously been developed in compliance with the DETR Applicants Guide [2]. The Part III sets out safe fissile mass limits and associated constraints (i.e. constraints on isotopic composition or on the presence of specified reflector materials) for 500 litre drum waste packages. The safe fissile mass limits for the RSTC were determined for a small set of bounding payload specifications.

These limits and constraints have been used to underpin the disposability assessment of numerous waste packaging proposals. Since the development of the SWTC family of designs, the RSTC Part III has continued to be applied as the limits have been considered to be relatively insensitive to the changes in transport container design.

The RSTC Part III was developed on a simple basis with the safe fissile masses derived from models of stillages of four part-crushed 500 litre drums, each containing aligned hemispheres of optimally moderated fissile material surrounded by shells of reflecting material (see Figure 2). These arrangements are highly contrived and for many waste packages are unduly pessimistic depictions of the geometry of the fissile material within the waste packages. In consequence the safe fissile mass limits defined by the RSTC Part III are highly restrictive. Where a waste packaging proposal has been found to exceed the limits and constraints of the RSTC Part III, a package specific criticality safety assessment has been developed. This justifies a less restrictive safe fissile mass for that specific waste package by taking credit for its known features, for instance knowledge of the isotopic composition, for the presence (or absence) of certain materials, or for the geometry of the fissile material and other materials that may be present. Thus a catalogue of package specific criticality safety assessments has been generated justifying the transport safety of specific waste packages that exceed the limits of the RSTC Part III.

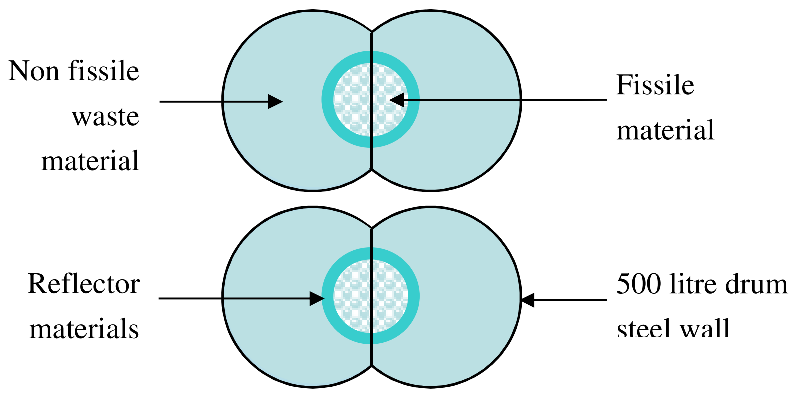

Figure 2: Plan view of the RSTC fissile material arrangements

Since developing the SWTC family of transport packages, RWM has been pursuing efforts to develop an SWTC Part III with less restrictive safe fissile mass limits.

Objectives

The principal objective of the work is to develop the safe fissile mass limits for the SWTC family of transport packages for use in informing the disposability assessment process. That is the process by which RWM advises waste producers on the suitability of waste packages being created now for future transport.

The SWTC Part III must provide confidence that waste packages manufactured in compliance with the limits specified can be transported in the future. Thus there must be confidence that:

- The SWTC Part III has been developed using a high quality process and the limits specified therein are free from error.
- That adherence to the limits specified in the SWTC Part III will result in waste packages (and criticality compliance assurance documentation for those waste packages) that can meet the requirements of a Competent Authority Certificate of Approval at the time of transport, decades from now.

A secondary objective of the SWTC Part III is to define less restrictive limits than for the RSTC Part III in order to minimise the need for package specific criticality safety assessments. If achievable, it is expected that this will provide best value to RWM and waste producers by minimising the need for additional and duplicate criticality safety analyses and will remove a perceived barrier (in the waste packager's mind) in developing waste packaging proposals for high fissile content wastes that exceed the current generic safe fissile mass limits.

Approach in defining less restrictive safe fissile masses

The selected approach is to increase the number of scenarios for which a safe fissile mass is defined and to better align those scenarios with the known properties of waste packages. It is hoped that this approach will allow a more appropriate safe fissile mass to be assigned to each waste package, increasing the safe fissile mass where possible and minimising the number of waste packages that fall outside the generic limits.

A report has been produced that sets out, at a high level, the methodology to produce an SWTC Part III [3]. The methodology recommends numerous enhancements to the RSTC Part III approach, including:

- Introducing additional fissile material bands and better alignment of those bands to UK wastes.
- Introducing additional waste geometry scenarios.
- Applying more realistic compositions and densities of possible contents.
- Providing consideration of mixing of 500 litre drums that adhere to different safe fissile mass limits within a transport container.

Progress to date

Building upon this methodology a preliminary SWTC Part III for a content of a disposal stillage containing four 500 litre drums has been developed [4]. The SWTC Part III justifies safe fissile masses for:

- Three 500 litre drum designs (monolithic or annular grouted with two annuli dimensions).
- Five fissile material groups.
- Three fissile material geometries.
- An upper and lower band of special reflector (i.e. beryllium or graphite) content.

This approach has resulted in the specification of ninety scenarios for which a safe fissile mass is defined. It has also resulted in the need to specify compliance rules in order to determine which safe fissile mass can be attributed to each waste package. The full list of criteria and proposed compliance rules are set out in Table 1.

It may be noted that the Irradiated Natural Uranium band has been split into two bands:

- Irradiated natural uranium up to 1% enrichment. This was increased from 0.81% in the RSTC Part III to cover slightly enriched fuels.
- Irradiated natural uranium up to 1.9% enrichment. This was added to represent wastes with increased concentrations of plutonium[1]. Such wastes had previously been assigned to the Low enriched uranium category (up to 5% enrichment) resulting in very restrictive safe fissile mass limits.

In addition, separate limits have been defined for High Enriched Uranium and for Plutonium, whereas previously these had been combined.

The three groups of fissile material geometry have been defined in order to allow waste packages to be assigned a safe fissile mass appropriate to the geometry of the waste.

The "Well mixed" group has been introduced to represent wastes that are essentially uniformly spread throughout a waste package. This group is intended to represent waste types such as ion exchange resins, sludges, raffinates, flocculants or other similar waste types. A typical packaging approach for these wastes would be in-drum mixing of the waste with a cementitious grout resulting in a high degree of assurance that the waste will be evenly distributed throughout. In the underpinning criticality calculations this group has been represented as a uniform heterogeneous fissile matrix (of optimum fissile particle size) (see Figure 3).

The "Limited non-uniformity" group has been introduced to represent wastes that are clearly not uniform, but that are distributed throughout the waste package to some known degree. This group was defined as an intermediate group between essentially uniform and the worst case (part sphere). A candidate waste type for this category would be fissile nuclide contaminated materials in super-compacted pucks. These wastes consist of miscellaneous materials with fissile nuclide surface contamination that is loaded into sacrificial drums and super-compacted. The super-compacted drums (or pucks) are then loaded into a waste drum and fixed in place with a cementitious grout. In this case the waste is not essentially uniformly distributed, but neither could it contain a hemisphere

---

1 The irradiation of natural uranium in a thermal reactor results in a higher concentrations of plutonium at the surface of the fuel element (the embleton layer). If this layer is preferentially separated (e.g. by corrosion of the fuel or deliberately as part of reprocessing) the separated fissile material can have properties similar to low enriched uranium.

of fissile material. In the underpinning criticality calculations this group has conservatively been represented as a slab of heterogeneous fissile material (of optimum fissile particle size) with a slab of special reflector above and below (see Figure 3).

The "Unlimited uniformity" group was included to represent wastes for which any limits on the distribution cannot be demonstrated. As with the RSTC Part III, this group has been represented as a worst case geometry of a hemisphere of heterogeneous material (or optimum fissile particle size), surrounded by a shell of special reflector and located at the mid-height of a drum such that two sets of two drums in a stillage of four align to form two spherical geometries (see Figure 3).

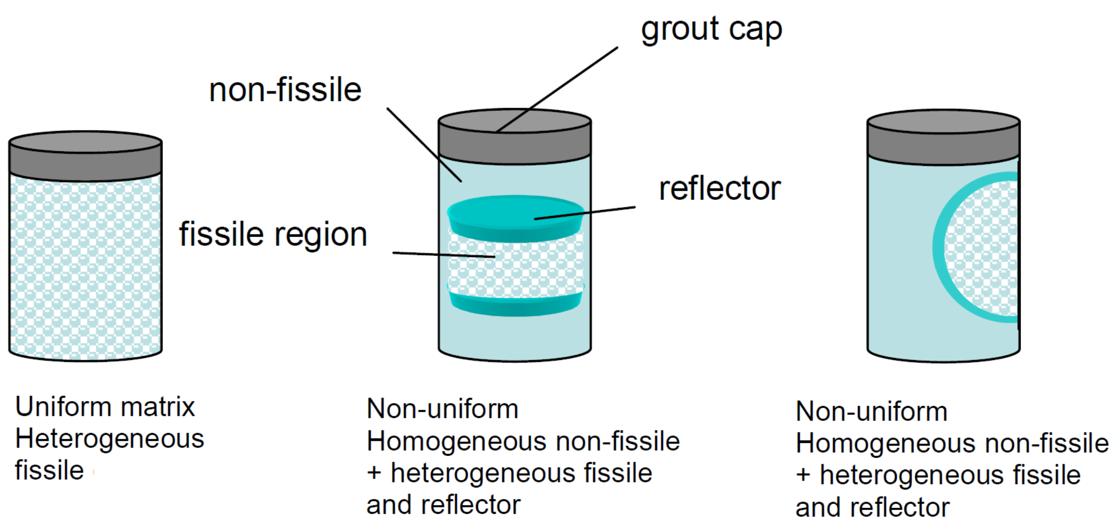

Figure 3: SWTC Part III waste geometries

Results of the preliminary SWTC Part III

The specification of more scenarios for which a safe fissile mass is derived has resulted in the definition of less constraining safe fissile masses for waste packages when credit can be taken for the geometry of the fissile material in the waste package. Specifically, when compared to the safe fissile masses for the "Unlimited non-uniformity" group:

- The safe fissile masses for the "Limited uniformity" group are a factor of two to eight greater.
- The safe fissile masses for "Well mixed" group are a factor of four to sixteen greater.

In addition the safe fissile masses for the new Irradiated Natural Uranium grouping at 1.9% enrichment are factor of 1.3 to 2 greater than those defined for Low Enriched Uranium group. Thus the work has met its objective in defining significantly less restrictive limits than for the RSTC Part III. However the work has run into difficulties in demonstrating that the regulatory requirement for optimisation[2] of parameters for which the value is unknown has been met (paragraph 676 of the IAEA Regulations for the Safe Transport of Radioactive Material [5]). For this reason the SWTC Part III has been issued as a preliminary report, to document the work undertaken thus far and to provide a breakpoint in order to determine a practicable way forward in further developing the SWTC Part III.

Approach to optimisation of parameters for which the value is unknown

The approach taken in the primarily SWTC Part III is a traditional response to paragraph 676 of the IAEA Regulations for the Safe Transport of Radioactive Material [5], which states:

> "*Where the chemical or physical form, isotopic composition, mass or concentration, moderation ratio or density, or geometric configuration is not known, the assessments of [single packages and arrays of packages in normal and accident conditions] shall be performed assuming that each parameter that is not known has the value that gives the maximum neutron multiplication consistent with the known conditions and parameters in these assessments.*"

This means that every parameter that is not constrained by the transport package design, or by the waste package compliance rules, must be assessed to find the value which provides maximum neutron multiplication (or indeed, the minimum safely subcritical mass). This approach deterministically demonstrates that a transport package remains sub-critical during transport by demonstrating that any conceivable combination of parameter values is sub-critical.

The Part III justifies the safe fissile masses by reference to reports setting out underpinning neutron transport calculations [6, 7]. In order to limit the time required to perform each calculation, and to limit the number of calculations required to a manageable number, it was necessary to apply a number of conservative simplifying assumptions to the design, such as omitting the drum internal furniture or details of the transport container design from the models.

Nevertheless, a large number of neutron transport calculations were required in order to:

- Determine the safe fissile mass for normal and accident conditions.
- Select the variant of SWTC used to determine the safe fissile masses.
- Optimise the moderator to fissile nuclide mass ratio.
- Optimise the fissile material particle radius and concentration.
- Optimise the non-fissile and cap grout material that may be present (from a candidate list of

---

2 In this paper optimisation is used to mean "identification of the parameter value that maximises neutron multiplication".

plausibly present materials).
- Evaluate the effect of 500 litre drum deformation.
- Optimise the position of the fissile material within a drum (for the spherical and slab cases).
- Evaluate the impact of arrays of transport packages.
- Evaluate the effect of water flooding density in the transport container cavity.
- Evaluate the effect of a release fraction of material in an accident.
- Evaluate the effect of mixtures of high enriched uranium and plutonium in the same drum.
- Evaluate the effect of mixtures of 500 litre drums that adhere to different safe fissile mass limits within a transport container.

Notwithstanding the significant extent of parameters considered above, verification of the preliminary Part III identified a further thirty one parameters that had not been fully optimised. A qualitative evaluation of those parameters would indicate that they, for the most part, would have only a very small influence on the neutron multiplication factor. Nevertheless, to progress with the existing approach, further work would be necessary to evaluate or optimise the effect of those parameters. Once complete the approach would need to be rolled out to the other waste package design types that may be transported into an SWTC (currently five additional waste package designs with two further variants proposed).

Thus continued progression under the existing approach will lead to a requirement to undertake a very large number of calculations. When compared to the simpler approach taken in producing the RSTC Part III, it can be seen that efforts to introduce more scenarios and especially to define more realistic waste geometries has resulted in a steep increase in the effort required.

Ultimately a potential conclusion for this work is that attempts to define less restrictive safe fissile masses generically, whilst applying the traditional response of paragraph 676, results in a steep increase in effort and that the best value approach is to retain a simplified generic assessment and restrictive safe fissile mass limits. In considering whether this is the case, RWM proposes to review whether the “bottom-up” approach to optimisation in the preliminary SWTC Part III is appropriate, or whether an alternative approach is viable.

The role of optimisation of unknown parameter values in ensuring safety

The effect of paragraph 676 is that, on an individual basis, each parameter value is either a necessary simplifying assumption or a bounding (although perhaps improbable) value for the parameter. Taken as a whole, this approach results in:

- Models that aggregate conservatisms.
- A need to undertake a very large number of calculations to identify the optimum parameter

values.

- A very large safety margin between a real waste package and the system modelled.

For example, in the case of the calculations underpinning "Unlimited non-uniformity" geometry safe fissile masses, the preliminary SWTC Part III currently assumes that each waste drum contains a hemisphere of fissile material composed of fissile particles of optimum size and pitch, optimally moderated, surrounded by a shell of reflector and then by a selection of non-fissile material that optimises neutron multiplication. It is assumed that an SWTC contains four such drums, with two sets of two drums aligned to create two spherical geometries. These hemispheres are located at the mid-height of each drum and at the correct radial position to align and to form two spheres. In accident conditions we assume that an impact results in compression of the drums such that four hemispheres come closer together. The caveats in the SWTC Part III identify that the system could be further optimised by fine tuning the height of the part spheres such that the balance between the reflection within the non-fissile waste and the interaction between an array of SWTCs is optimised. Additionally the system could be further optimised by tuning the radial position of the part spheres such that the interaction between the two hemispheres in each sphere, and between the two spheres is optimised. It is not expected that either of these parameter values would have a significant influence on the safe fissile mass. Nevertheless, paragraph 676 may be interpreted to mean that they must be fully investigated.

From a "top-down" perspective it can be judged that the "Unlimited non-uniformity" model in the preliminary SWTC Part III is already highly contrived and is a highly pessimistic representation of a waste package. It can be argued that the further "bottom-up" fine tuning of the unknown parameter values would not result in a safety benefit, as the safe fissile masses defined by the preliminary SWTC Part III are already based upon a model that is sufficiently conservative so as to deterministically demonstrate that the waste packages would remain sub-critical during transport. Moreover the level of refinement in the model is arguably already disproportionate to the achievable accuracy of measurement techniques needed to ascribe a fissile nuclide mass to a waste package. Thus it could be argued that the traditional approach to optimisation in response to paragraph 676 is not fit for purpose when applied to fissile waste packages where many parameters are uncertain, as it leads to a highly disproportionate level of pessimism in the model when viewed as a whole.

A way forward

The IAEA Transport Regulations ensure that the transport of radioactive material is deterministically safe. The traditional approach to optimisation of uncertain parameters in response to paragraph 676 is an exhaustive "bottom-up" assessment. Where the number of unknown parameter values is low, this is a pragmatic approach that ensures that a transport package is deterministically safe through ensuring that the safe fissile mass is sub-critical for any conceivable combination of parameter values.

For an assessment of wastes, where the number of uncertain parameters is great, the “bottom-up” approach ceases to be a pragmatic approach. It results in:

- Models that aggregate conservatisms.
- A need to undertake a disproportionately large number of calculations to identify the optimum parameter values.
- A very large safety margin between a real package and the system modelled.

Application of this response to paragraph 676 to materials defined as non-fissile by paragraph 222 could, erroneously, result in the conclusion that these materials are not safely subcritical. The IAEA advisory materials [8] explains that the safety basis of paragraph 222 is justified by qualitative judgements that the conceivable instances where the material may be postulated to be unsafe could not credibly occur. Thus in this case, the regulatory interpretation of deterministically safe can be inferred to mean, safely subcritical in any credible scenario.

It can be argued that a similar logic should be permitted to be applied to the criticality safety analysis of fissile packages where the number of parameters with unknown values is great. Specifically, such an approach could allow an applicant to limit the assessment of some parameter values where it can be justified that the assessment is already sufficiently conservative so as to ensure that the package will remain safely subcritical. It is envisaged that such an assessment would need to take a “top down” view, in order to consider the level of conservatism in the model as a whole.

Conclusions

This paper describes RWM’s progress in developing an SWTC Part III. It describes RWM’s attempts to define less restrictive safe fissile masses for waste packages by taking credit for more known properties of the wastes (subject to compliance rules). It identifies the difficulties of applying the traditional “bottom up” approach to optimising unknown parameter values in a transport criticality safety assessment for waste where a great number of parameter values are unknown. It proposes that it may be appropriate to develop an alternative approach to optimisation of unknown parameter values.

Acknowledgments

The authors would like to acknowledge the contributions of Michelle Nuttall and Dominic Winstanley of Sellafield Ltd in development of the preliminary SWTC Part III.

Table 1: Proposed compliance rules for the preliminary SWTC Part III

Criterion	Options and compliance rule	Information
1 Fissile Group	**a. INU(1)** Mass U235 equivalent ≤ 1.0% mass U **b. INU(2)** Mass U235 equivalent ≤ 1.9% mass U **c. LEU** Mass U235 equivalent ≤ 5% mass U **d. HEU** Mass U235 equivalent > 5% mass U **e. PU** Mass Pu > 10% mass U235 (excluding INU)	Only a single fissile group can be applied to each drum and this must be the group that bounds all fissile nuclides in the drum. "U235 equivalent" = U235+1.6×Pu This equivalence formula should not be used for the LEU or HEU fissile group if Pu > 10% mass U235, in which case the PU fissile group should be used. This equivalence formula should not be used for the INU(1), INU(2), LEU or HEU fissile group if the Pu is not materially inherent to the U, in which case the PU fissile group should be used. The PU fissile group may be applied to any mixture of Pu + U235 + U233 using the equality: $Pu_{equivalent} = Pu + U233 + 0.65xU235$ where the value $Pu_{equivalent}$ must comply with the Pu limits.
2: Drum type	**a. Standard drum (monolithic)**: Waste region occupies full footprint of the waste package. Grout cap not deeper than 18 cm. **b. Annular grouted drum (7 cm)**: Waste package incorporates a grouted annulus (around sides and on base of drum) not thicker than 7 cm. Grout cap not deeper than 18 cm. **c. Annular grouted drum (12 cm)** Waste package incorporates a grouted annulus (around sides and on base of drum) not thicker than 12 cm Grout cap not deeper than 18 cm	

Criterion	Options and compliance rule	Information
3: Fissile material geometry	**a. Well mixed** The fissile nuclides must be well mixed (i) with the other constituents of the conditioned waste and must be evenly distributed (ii), (iv) throughout the conditioned waste region (iii) in the drum. **b. Limited non-uniformity** The fissile nuclides must be evenly distributed (ii), (iv) across the footprint of the conditioned waste region (iii) in the drum. **c. Unlimited non-uniformity** Any distribution of fissile nuclides and other constituents in the drum.	(i) This might be achieved through a waste conditioning process, e.g. tumble mixing, stirring, shredding or pulverising. (ii) This does not mean 100% uniformity. Small random variations in the fissile nuclide concentrations from point to point are acceptable. (iii) The internal region of the drum not occupied by the grout cap and any grout annulus. (iv) Distribution must be maintained throughout all conditions of transport, e.g. fissile nuclides are fixed by grouting of waste.
4: Special reflectors	**a. Low reflector content** Mass of beryllium ≤ 900g Mass of graphite ≤ 900g **b. High reflector content** Mass of beryllium ≤ 90kg Mass of graphite ≤ 175kg	The limits on Be or graphite apply when only one of the elements is present in the drum. If both are present then their combined mass must not exceed the lesser of the two individual limits.

References

1. Nirex, Part III – *Additional Design Requirements for Fissile Packages*, T/REP/20395 Issue E/03, May 1998.
2. DETR, *Guide to an Application for UK Competent Authority Approval of Radioactive Material in Transport (IAEA 1996 Regulations)*, DETR/RMTD/0003, January 2001.
3. AREVA RMC, *Methodology Development for the Criticality Component of the Design Safety Report for the Standard Waste Transporter Container SWTC-285*, R08-041 (A) Issue C, August 2012.
4. Sellafield Ltd, *Part 3: Additional Design Information Required for Fissile Materials – Response to the Department of Transport's Guide for Transport of ILW Wastes in the Standard Waste Transport Container (SWTC-70 and SWTC-285)*, CDSA/SWTC/CR01 Issue 1, March 2015.
5. IAEA, *Regulations for the Safe Transport of Radioactive Material - 2012 Edition*, SSR-6.
6. Sellafield Ltd, *MONK Scoping Calculations Study to Support a Transport Licence Application for the Standard Waste Transport Container carrying 500 litre Drums*, SCN-340

Issue 1, February 2015.

7. Sellafield Ltd, *Monk Calculations Study to Support a Transport Licence Application for the Standard Waste Transport Container carrying 500 litre Drums*, SCN-336 Issue 1, March 2015.
8. IAEA, *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2012 Edition)*, SSG-26.