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The transport criticality assessment of fissile wastes: Issues, developments and suggestions.

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WNTI and RAMTUC

Two organisations have been particularly concerned to promote the development of a set of fissile exceptions which are appropriate for wastes, and these are WNTI and RAMTUC. It is appropriate to briefly describe these organisations and the role that they play in the RAM transport world:

WNTI: [WNTI, 2009] was founded in 1998 by British Nuclear Fuels plc (BNFL) of the United Kingdom, COGEMA of France, and the Federation of Electric Power Companies (FEPC) of Japan to represent the collective interests of the RAM transport sector, and also those who rely on safe, effective and reliable transport. Over the past few years, WNTI has grown dramatically with member companies drawn from a wide range of industry sectors, including major utilities, fuel producers and fabricators, transport companies and package producers.

In 2004, WNTI set up a Criticality "Task Force" to promote standardisation of the methods and data used by industry in TCA. The WNTI Criticality Task Force is also concerned with the transport of waste materials and has representation on the IAEA working group. The benefit of this has been that the working group has been directly informed by international experience in waste TCA.

RAMTUC [RAMTUC 2009] is another organisation which has contributed to the IAEA initiative. This is the UK industry's forum for development of strategy and policy for the safe transport of RAM. Membership includes all of the major nuclear organisations within the UK. RAMTUC's main contribution has been to set up a UK working party to collate experience and views and to communicate these to the IAEA, via the UK DfT.

The difficulties with traditional TCA

Within Europe, the transport of fissile materials (i.e. plutonium, uranium) is carried out in accordance with the IAEA Regulations [IAEA 2005]. The Regulations were first published nearly fifty years ago in 1961, when the transport of primary fuel-cycle (aka "front-end") materials (e.g. uranium ores, fuel assemblies, fissile powders etc) were the principal concerns. If uncontrolled, the transport of these kinds of fissile materials would pose a high criticality risk because they are concentrated and unadulterated by diluents and neutron poisons. In some circumstances a criticality could be achieved with small (theoretically < 0.5kg) quantities of the fissile material.

In contrast, fissile wastes usually present a much lower criticality risk. Generally, the wastes are very different in nature from the front-end materials for the following reasons:

- The mass of fissile material per package is small compared to the critical quantity.
- The average concentrations of fissile material are very low and much smaller than infinite sea concentrations[1].
- The waste matrix often contains a large proportion of diluents and neutron absorbers.

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[1] This is the concentration below which criticality becomes impossible even with unlimited quantities of the material, i.e. $K_\infty < 1$.

These factors mean that, even under the most extreme circumstances, criticality is generally much less likely than with primary fuel-cycle materials. However, the characteristics of fissile waste can lead to difficulties in the following three areas:

- Criticality modelling under the IAEA Regulations.
- Compliance with the requirements of the IAEA Regulations.
- Making the overall risks ALARP (ALARA).

Criticality modelling under the IAEA Regulations

The criticality assessment methodology prescribed the IAEA Regulations for licensed packages [IAEA 2005, paras 677- 682] is well defined, and strongly encourages the criticality assessor to assume that for all parameters "worst-case" values are assumed for the purposes of criticality modelling. This approach is deeply embedded in the culture of TCA, to the extent that most assessors would not consider any other approach. Typically, the fissile and moderating materials are assumed to form a spherical geometry, in a concentration and in positions within the package which maximise the neutron multiplication factor, with a close-fitting thick neutron reflector and all non-verifiable neutrons absorbers and diluents ignored. Any form of realism in the modelling is normally avoided.

This philosophy is entirely sensible for higher-risk materials, such as fissile powders and fuel pellets, but far less appropriate for many waste materials. For fissile wastes, these assumptions can often be wholly unrealistic, representing a triumph of academic consideration over reality. For example, in plutonium contaminated waste materials, it is difficult to imagine a credible accident that could form the waste into a configuration resembling an optimally moderated and reflected sphere, devoid of diluents and neutron absorbers. This kind of approach results in package fissile limits that can be very restrictive for transport.

An example of this is currently provided by two licensed Type B packages. One, a large waste container (of many m3 in volume), is permitted to carry up to about 400 g Pu, whilst the other, a much smaller package (tens of litres), is permitted up to 18 kg PuO2 powder. These are not contrived examples, but licensed packages which are in use today.

Compliance

It is a requirement under the IAEA Regulations that the Consignor must be able to demonstrate compliance with package fissile limits and any other characteristics which are credited in the certificate. Waste materials can create difficulties for compliance in two areas: (i) fissile assay and (ii) verification of waste characteristics.

Fissile monitoring (both gamma and neutron) can be can be difficult for wastes because of factors like:

- Self-shielding in lumped fissile materials
- Shielding by bulk waste materials
- Contamination by non-fissile species
- The distribution of fissile material in the waste.
- Non-uniform isotopics.
- Shape and size of containers

Safety factors can be derived to ensure that the probability of an under-estimate of the fissile material is very low, but often this will be highly penalising for the majority of the waste packages. Experience has shown that the safety margins in the final assay values for waste packages can be very large indeed.

More generous fissile limits may sometimes be derived in TCA by taking account of specific characteristics of the waste. For example, credit could be taken for neutron absorbers or diluents in the matrix. For mixed waste-forms, such as Plutonium Contaminated Waste Materials or contaminated metals, the question arises as how to demonstrate compliance with the assumptions made in the criticality assessment. Clearly, in a large waste stream it is impracticable to sample every package. Indeed for large packages, it can be difficult to ensure that a sample is representative of the package as a whole.

In other industries, statistical methods would be routinely used for situations such as these. The general approach would be to produce a sampling plan (ie % of waste stream to be sampled and how to sample it) based on a statistical confidence level and the inherent variability of waste. However, there is no guidance as to an appropriate approach in the IAEA suite of safety documentation. In the authors view, this is an area which is ripe for development and cooperation with Competent Authorities.

ALARP (ALARA)

Over-pessimism in the TCA is undesirable because it can lead directly to an increase in other types of risk, but with very little real benefit in terms of criticality safety. For example, overly pessimistic fissile limits could result in:

- More waste transports than are really needed – this increases the potential for conventional (i.e. non-nuclear) risks such as road transport accidents.
- Package splitting to meet criticality limits, which will result an increase in radiation dose and conventional handling hazards to operators. This would also result in the creation of additional ("secondary") wastes (e.g. PPE).
- Additional costs to industry.

Developments in the Fissile Exception criteria

Currently, certain fissile materials may be excepted from the requirements for packages containing fissile material (IAEA 2005, para 672). "Fissile exception" is a useful facility; obtaining a license for a package containing fissile material is time consuming and costly because of the criticality assessment process itself and also because of the additional requirements that are placed on packages containing fissile materials (IAEA 2005, para 671).

Currently, the criteria of most interest to waste shippers are essentially based on a consignment mass (e.g. ≤ 400 g) in conjunction with a low package fissile mass (≤ 15g) or a or a restriction on fissile concentration (≤ 5g in 10 litre), or very low uranium enrichments (< 1%). Many waste streams fail to satisfy these criteria, whilst having demonstratively large safety margins in terms of K_∞.

The proposed fissile exceptions Developing a new set of fissile exceptions which are simultaneously practical, self-consistent, and appropriately (i.e. adequately, but not overly) safe is has been difficult. Part of the difficulty is that the current fissile exceptions are based on an unrelated set of ideas, with different levels of safety. A complicating factor is that any new regulations should not disadvantage the existing shipping arrangements, which have so-far proved themselves to be safe in use. The "exceptions" debate has been going on for a decade or more, with most proposals failing to reach consensus.

Recently, progress has been achieved. The IAEA's Transport Safety Standards Committee (TRANSSC) has formed an international working group. The UK Competent Authority has taken the lead in setting up a programme to review the fissile exceptions and make recommendations for improvement.

Specialists on transport and criticality safety from the UK, USA, France, Germany, Spain, Sweden and Japan have met several times over the last two years, most recently in Vienna, February 09, and before that in Chester UK in April '08, to discuss possible amendments. The Chester meeting was particularly important as it was here that many of the ideas were first developed; also, the IAEA specialists took the opportunity to examine the waste handling/packaging operations at Sellafield Ltd Capenhurst site.

The process for setting a new criterion for excepting fissile material has not finished, but a proposal for a new set of exceptions has been presented to the IAEA and is now undergoing its "120-day" review. (This gives the member states of the IAEA the chance to consider and comment on the proposal.) If all goes well the new criteria will feature in the 2013 edition of the Transport Regulations, or perhaps later if the IAEA choose to defer publication. In the meantime, provided that the IAEA accept the criteria, the UK DfT have indicated that they will be sympathetic to their use in the UK, although the means of implementation in the UK has not been finalised.

An outline of the proposal is presented in Tables 1 and 2. The new criteria have been designed to (mainly) preserve existing transport arrangements, whilst making available new types of exception and providing greater flexibility, especially for uranium of low enrichment. The scheme has been derived from robust safety principles. Please note that both the words and values (and perhaps even specific elements of the scheme), may change as a result of the "120-day" review. The proposal is reproduced here to alert waste consignors and package designers of the new fissile exceptions that may soon become available.

Principally the new provisions will include:

- De minimis value of 0.25 g of fissile material per package (see item 222(c) of Table 1). There are no other restrictions attached to this criterion.
- Package-independent criteria. The revised regulations are likely to contain criteria which depend only on the material being shipped (see items 417(c) and (d) of Table 1). Here criticality safety will be maintained by the inherent properties of the material itself and so there is no need to place requirements on the behaviour or characteristics of the packages. This is possible either because the material $K_\infty < 1$ or, if $K_\infty < 1$, the quantity required for criticality would exceed any credible amount even under extreme accident conditions.
- Package mass criteria. Essentially, these criteria (see Table items 672) describe a set of "pre-assessed" package limits for a number of fissile and moderating materials. These packages will require labelling (see Table 1 item 539).

  There are limits in item 672 for packages which cannot be shown to pass the package performance tests for normal conditions of transport (NCT) and also limits for packages which can be shown to pass the tests. These new criteria replace the old "15g & 400g"criterion. The methodology which underpins the scheme is entirely consistent with the "5N/2N" criticality assessment methodology used for licensed packages This is important because it gives assurance that at least the same degree of criticality safety is present in fissile excepted packages as in CA licensed ones. The scheme mainly preserves current shipping arrangements, yet allows consignors of low-enriched uranium to benefit from the lower criticality hazard posed by these materials.

  An additional feature of the scheme is that it allows consignors to gain advantage from packages that can be shown to withstand the tests for the NCT. For example, item 672((b) shows that for U as U(1.5) in packages which pass the NCT tests, a consignment could contain up to 5 packages, with each containing up to 240 g U235 in a substrate no more efficient as a moderator than water. In comparison, for packages which cannot be shown to pass the NCT test, item

672(a) shows that a package would be limited to 96 g U235. These values contrast markedly with the current TS-R-1 provisions, under which, a consignor would be limited to no more than 26 packages with 15g U235 per package. (Consignors could ship up to 20 packages, each with 15 gU235 under the new scheme).

The "Y&Z-values" in Table 2 are based on criticality models of transport packages containing fissile materials in "worst-case" geometrical configurations, taking account of typical packaging materials, considering all possible fissile concentrations and simulating accident conditions. Sellafield Ltd carried out approximately 100,000 criticality calculations to underpin these values [Sellafield 2009] and these were cross-checked against French and Swedish studies. (It is expected that a full report of the criticality modelling will be published at a later date.)

- National arrangements agreed with the Competent Authority and subject to multilateral approval (see Table 1, item 417e). If ratified by TRANSSC, this form of exception could be immensely powerful. It is envisaged that the consignor would put together a "mini" criticality assessment justifying the particular materials for exception. New guidance material, published along with the new edition of the regulations will explain how this criterion can be used in practice. Briefly, excepted materials must have $K_\infty < 1$ or, if $K_\infty < 1$, the quantity required for criticality would exceed any credible amount. The consignor will need to provide a robust demonstration that the K_∞ would not be significantly increased by any inhomogeneities in the waste and by the effects of an impact or fire, or by the addition of water. In the author's view, it is likely that additional guidance material will be made available to criticality assessors through the UK Working Party on criticality.

Note Readers who currently transport material as fissile excepted will have noticed that the criterion excepting packages having less than 5 g of fissile material in any 10 litres of volume (subject to a consignment limit – see IAEA 2005, para 672(a)(iii)) is not included in the proposal.

Despite its widespread use (at least within the UK) the IAEA Working Group felt that this type of exception could no longer be supported. The main reason is that the ratio (<5g in 10 litres) cannot guarantee criticality safety. There is no restriction on the material providing the 10 litre dilution. It could be void or plastic and offers no safety in the event of an accident (e.g. plastic materials could be removed by a fire or be compressed in an impact). It is recommended that consignors currently using this criterion study the proposals in detail.

Other ideas

In many countries, the regulation of fissile wastes is the responsibility of more than one regulatory body. There is a concern that for some fissile wastes this could result in approvals for one phase (e.g. to generate and store waste), but a non-approval for another phase (e.g. for transport), leading to orphan waste packages and rework. (Regulation stability is also an issue of concern).

The suggestion of a holistic approach to the regulation of wastes is currently under discussion by a number of waste and criticality experts. It is envisaged that this would involve a joint decision by all regulators as to the acceptability of a transport application based on a consideration of all waste phases, i.e.: generation, packaging, storage, transport and disposal (if appropriate).

A closely related idea is that of a single integrated safety case, which would address, as far as is practicable, the safety for all phases of the waste life-cycle.

The benefit of holistic regulation and an integrated safety case approach for fissile waste transport would be that:

- Regulators would gain a better understanding of the waste package arrangements (e.g. package, materials and fissile limits), criticality and other risks, and the reasons why certain decisions had been taken.
- It would be easier to present the arguments for an optimised (i.e. ALARP) approach to safety (i.e., over all phases, and for both radiological and non-radiological risks).
- A safety assessment process which is simpler, more efficient and less costly.

Conclusions

This paper has:

- described the main issues for the transport of fissile wastes.
- given an outline of a proposal for revised criteria for the exception of certain materials and packages from the requirements of the IAEA Regulations in respect of fissile material. This proposal has been presented to the IAEA and is undergoing the 120-day review.
- alerted consignors to the likely disappearance of the "5g in 10 litre" fissile exception.
- suggested that an integrated safety case approach to fissile wastes (generation, packaging, storage, transport and disposal) and holistic regulation would have benefits for all, i.e.: waste producers, consigners and regulators.

References

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2. Radioactive Material Users Committee, www.ramtuc.org.uk
3. IAEA Safety Standards Series, TS-R-1, Regulations for the Safe Transport of Radioactive Material 2005 Edition.
4. IAEA Safety Standards Series, TS-G-1.1 (ST-2), Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material
5. Sellafield Ltd (2009), S&RM/CDSA/Fissile Exceptions/CR01Criticality Calculations In Support of The DfT Proposal On Fissile Exceptions To TRANSSC, WP Darby, DM Nuttall, J Onakanmi

Table 1: The Proposed Fissile Exceptions

Note: this scheme has been proposed to, but not yet been accepted by, the IAEA. The original text can be found in the IAEA document:

> IAEA 2013 – TM 37068, "Proposed TS-R-1 text related to fissile material exceptions and packages containing fissile material that would be excepted from multilateral approval"

#	Proposed Regulatory Text	Comment
222	*Fissile nuclides* shall mean uranium-233, uranium-235, plutonium-239~~,~~ and plutonium-241. *Fissile material* shall mean a material containing any of the *fissile nuclides*. Excluded from the definition of *fissile material* are: (a) *natural uranium* or *depleted uranium* which is unirradiated, and (b) *natural uranium* or *depleted uranium* which has been irradiated in thermal reactors only. (c) material in *packagings* containing up to 0.25 g of *fissile nuclides* in any form. *Fissile-excepted* refers to *fissile material* that complies with subparas 417(a)-(e).	(c) is new
417.	*Packages* containing *fissile material* shall be classified under the relevant entry of Table 1 (of TS-R-1) for *fissile material* unless the material being carried meets one of the conditions in subparas (a) – (e) below. Only one type of exception is allowed per *consignment*. (a) Uranium enriched in uranium-235 to a maximum of 1% by mass, and with a total plutonium and uranium-233 content not exceeding 1% of the mass of uranium-235, provided that the *fissile nuclides* are distributed essentially homogeneously throughout the material. In addition, if uranium-235 is present in metallic, oxide or carbide forms, it shall not form a lattice arrangement. (b) Liquid solutions of uranyl nitrate enriched in uranium-235 to a maximum of 2% by mass, with a total plutonium and uranium-233 content not exceeding 0.002% of the mass of uranium, and with a minimum nitrogen to uranium atomic ratio (N/U) of 2. (c) Low concentrations of *fissile nuclides* in solid non-fissile material (e.g. consolidated wastes, activated materials) in which: (i) The *fissile nuclides* are essentially uniformly distributed throughout a non-fissile solid or a collection of non-fissile solid objects, or is essentially uniformly distributed in a non-fissile solid compact binding agent (such as concrete, soil, ceramic, etc.); (ii) The *fissile nuclides* are relatively inseparable from the non-fissile material by leaching, burning or mechanical impact; and (iii) The average mass of *fissile nuclides* within the non-fissile solid does not exceed 1g fissile nuclides / 2000g of non-fissile solid. Lead, beryllium, graphite, and hydrogenous material enriched in deuterium may be present, but shall not be included in determining the required mass of solid non-fissile material. (d) Low concentrations of fissile nuclides in solid non-fissile material (e.g. consolidated wastes, activated materials) in which: (i) The fissile nuclides are relatively inseparable from the non-fissile material by leaching, burning, or mechanical impact; (ii) The average mass of fissile nuclides within the non-fissile solid, excluding any	(c) is new (d) is new (e) is new

	reflecting material, does not exceed 1g fissile nuclides / 200 g of non-fissile solid. Lead, beryllium, graphite, and hydrogeneous material enriched in deuterium may be present, but shall not be included in determining the required mass of solid non-fissile material. (iii) Individual packages shall not contain more than 15 grams of fissile nuclides. The packaging material shall not be included in the fissile – to – non-fissile ratio. (e) Other materials agreed with the *Competent Authority* and subject to *multilateral approval*.	
539	Each label conforming to the model in Fig. 5 (not provided) shall be completed with the *criticality safety index (CSI)* as stated in the certificate of approval for *special arrangement*, in the certificate of approval for the *package design* issued by the *competent authority* or as specified in paras. 672, 672bis1, or 672bis2.	New
672.	Packages containing fissile material that meet one of the provisions of subparagraph (a) to (c) are excepted from the requirements of paras 674-682 and 812. The packages must contain less than 500 total grams of Be, graphite, or hydogenous material enriched in deuterium. a) Packages containing fissile material in any form provided that: i. The smallest external dimension of the package is not less than 10 cm ii. The CSI of the package is calculated using the following formula: $CSI = 50 \times 5 \times \{[\text{mass of U-235 in package (g)}] / Z + [\text{mass of other fissile nuclides in package (g)}] / Y\}$ Where the values of Z and Y are taken from Table 2. iii. The CSI of any package shall not exceed 10. b) Packages containing fissile material in any form provided that : i. The *package*, after being subjected to the tests specified in paras 719–724, shall (a) retain its fissile material contents; (b) preserve the minimum overall outside dimensions of the *package* to at least 30 cm, and (c) prevent the entry of a 10 cm cube. ii. The CSI of the package is calculated using the following formula: $CSI = 50 \times 2 \times \{[\text{mass of U-235 in package (g)}]/ Z + [\text{mass of other fissile nuclides in package (g)}] / Y\}$ Where the values of Z and Y are taken from Table 2. iii. The CSI of any package shall not exceed 10. c) Packages containing fissile material in any form provided that : i. The *package*, after being subjected to the tests specified in paras 719–724, shall (a) retain its fissile material contents; (b) preserve the minimum overall outside dimensions of the *package* to at least 10 cm; (c) prevent the entry of a 10 cm cube.	(a) is new and for any packages (b) is new and for packages which pass the NCT tests (c) is new and for any packages - containing up to 15 g.

ii. The maximum mass of fissile nuclides in any package shall not exceed 15 g.

iii. The CSI of the package is calculated using the following formula:

CSI = 50 x 2 x {[mass of U-235 in package (g)]/ Z +
[mass of other fissile nuclides in package (g)] / Y}

Where the values of Z and Y are from Table 2 assuming uranium enrichment in weight percent to be 100.

Table 2. Proposed conveyance mass limits ("Y&Z" values) for packages containing fissile material that are excepted from multilateral approval

Fissile nuclide	**Uranium enrichment in weight percent of U-235 not exceeding**	**Fissile nuclide mass (g) mixed with substances having an average hydrogen density less than or equal to water**	**Fissile nuclide mass (g) mixed with substances having an average hydrogen density greater than water**
U-235 (Z)[i]	1.5	2400	2000
	5	1000	770
	10	810	550
	20	700	470
	100	540	360
Other fissile nuclides (Y)[ii]	Not Applicable	350	230

Notes:

i) If a package contains uranium with varying enrichments of U-235, then the mass corresponding to the highest enrichment value shall be used for Z

ii) Plutonium may be of any isotopic composition provided that Pu241<Pu240

iii) These values are subject to ratification by the IAEA and are provided only for information.

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