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Development of an application for approval of a design of material as fissile excepted

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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.

The 2012 edition of the International Atomic Energy Agency's Regulations for the Safe Transport of Radioactive Material introduces a major revision to the provisions for the transport of fissile nuclides in a package that is not Competent Authority approved to contain fissile material. A new provision allows multilateral approval of a design of material as fissile excepted. Many higher activity waste materials planned for disposal at a geological disposal facility are candidates for shipment under that provision.

RWM working together with International Nuclear Services and Sellafield Ltd has developed an application for material containing low concentrations of fissile nuclides. The application is generic and is intended to be applicable to a broad range of fissile nuclide bearing waste materials. This paper describes the development of RWM's application.

Introduction

The transport of radioactive material must comply with the requirements of the IAEA Regulations for the Safe Transport of Radioactive Material (Transport Regulations). The 2012 edition of the IAEA Transport Regulations [1] were issued in 2012 and were implemented in the UK in January 2015 through update of the international regulations.

The 2012 edition of the IAEA Transport Regulations introduce a provision permitting a Competent Authority to multilaterally approve a material design as fissile excepted. Such approval excepts material from the requirements for the transport of fissile material, notably controls on the design and approval of transport packaging for criticality safety, package accumulation control and implicitly the need for additional criticality safety assessment of each package design. Fissile exception approval requires an applicant to demonstrate that the material is safely subcritical without accumulation control in routine, normal and accident conditions of transport. Many fissile nuclide bearing waste materials are potential candidates for fissile excepted approval. RWM has identified an opportunity to attain a generic fissile exception approval covering a broad range of UK radioactive wastes. Working in conjunction with International Nuclear Services and Sellafield Ltd a fissile exception application for material containing a low concentration of fissile nuclides has been developed and submitted to the Competent Authority [2]. This application is a first of its kind in the UK.

The purpose of this paper is to describe the approach taken in the development of the fissile exception application.

Background

Regulatory context

The IAEA Transport Regulations specify graded requirements for package design and contents limits that are proportionate to the potential hazard of the radioactive material being transported. The controls to maintain subcriticality during routine, normal and accident conditions of transport are similarly graded in proportion to the criticality safety hazard of the material.

Packages containing material classified as fissile are subject to stringent requirements on their design and approval. They require:

1. Criticality safety assessment that deterministically demonstrates that the package (and arrays of packages) will remain subcritical in routine, normal and accident conditions of transport.
2. Approval by the Competent Authority.
3. Accumulation controls to be applied during shipment.

The deterministic approach to criticality safety assessment requires uncertainties in parameters such as physical form, isotopic composition, mass or concentration, moderation ratio or density, or geometric configuration to be dealt with by assuming each parameter to be at the value that gives the maximum reactivity. For waste materials this approach often leads to modelling an optimally moderated and reflected sphere of fissile material, resulting in very constraining contents limits. Alternatively, modelling of other non-worst conceivable scenarios can result in onerous characterisation and process requirements.

Packages containing material that is defined as non-fissile or that are classified as fissile excepted are not subject to the requirements for packages containing fissile material. Hence they do not need criticality safety assessment, competent authority fissile approval or accumulation control. Definition as non-fissile or classification as fissile excepted covers either small quantities of fissile nuclides that do not pose a criticality hazard or specific materials that are subcritical in any quantity. The key allowances in the 2009 edition in the IAEA Transport Regulations [3] in respect of fissile nuclide bearing waste were:

- The exclusion from definition as fissile of an unlimited quantity of natural or depleted uranium that may have been irradiated in a thermal reactor.
- A fissile exception for packages containing up to 15 grams of fissile nuclides, subject to a consignment limit of between 180 to 400 grams of fissile nuclides[1].
- A fissile exception for material containing up to 5 grams of fissile nuclides per 10 litres material, subject to a consignment limit of between 180 to 400 grams of fissile nuclides[1].

The historical impact of these limits was to significantly constrain the fissile nuclide content of packages designs that are not Competent Authority fissile approved.

Changes in the 2012 edition of the IAEA Transport Regulations

It has long since been recognised that large accumulations of packages each containing 15 grams of fissile nuclides, or of material containing 5 grams of fissile nuclides per 10 litres, both subject to a consignment limit (between 180 to 400 grams), presented a potential challenge to criticality safety. For example, imposing a mass limit on a consignment provides insufficient control for criticality safety, since the approach did not prevent the unintended mixing of multiple consignments during shipment. Furthermore the imposition of a mass limit per consignment further highlighted concerns with industry’s growing need for transport of what was perceived by many to be very low-risk fissile material (e.g. large volumes of waste products with very low concentrations of fissile nuclides).

The 2012 edition of the IAEA Transport Regulations provides a significant modification to the approach implemented for exceptions to the requirements for transport of fissile material. Due to the concerns cited above, the fissile exceptions for 15 gram of fissile nuclides per package and for 5 grams of fissile nuclides per 10 litres of material were removed from the 2012 edition. In their place the 2012 edition of the IAEA Transport Regulations specifies a range of new provisions. Most notably a provision that permits a Competent Authority to multilaterally approve specified material as fissile excepted.

[1] The consignment limit depends on the isotopic composition and presence of materials with a hydrogen density greater than water e.g. polythene.

Fissile exceptions for very low risk fissile materials

In producing the 2012 edition of the regulations the IAEA received numerous proposals for fissile exception criteria aimed at very low-risk fissile material. The approach receiving most discussion was proposed by the United States based upon the fissile exceptions already implemented in the United States' Code of Federal Regulations (CFR) [4].

As of 1996 the fissile exceptions in the United States' CFR were consistent with those in the IAEA Transport Regulations. Criticality safety assessment of a proposed shipment of beryllium oxide contaminated with high enriched uranium demonstrated that the fissile exception for 5 grams of fissile nuclide per 10 litres did not provide adequate criticality safety [5]. The Nuclear Regulatory Commission (NRC) contracted Oak Ridge National Laboratory (ORNL) to review the fissile exceptions and propose potential changes. ORNL's study [6] proposed an alternative exception based upon control of the ratio of non-fissile to fissile solid mass. The proposal was adopted into the US CFR and remains in force.

The US CFR fissile exception is as follows:

> "*Low concentrations of solid fissile material commingled with solid nonfissile material, provided that:*
>
> > *(i) There is at least 2000 grams of solid nonfissile material for every gram of fissile material, and*
> > *(ii) There is no more than 180 grams of fissile material distributed within 360 kg of contiguous nonfissile material.*
>
> *Lead, beryllium, graphite, and hydrogenous material enriched in deuterium may be present in the package but must not be included in determining the required mass of solid nonfissile material.*"

Ultimately an IAEA consensus on a definition of a fissile exception for materials containing a low concentration of fissile nuclides could not be reached. It was acknowledged that a definition of fissile exception that can be practicably applied to waste materials, which inherently have some uncertainty in the form, composition and disposition of the material, requires a move away from the historical deterministic approach of the IAEA Transport Regulations. Furthermore it was identified that it may be more pragmatic to define fissile exceptions on a local basis as, for instance if the source of a waste stream is well understood, the verification requirements can be adapted to that particular application and known properties of the actual fissile and other materials can be accounted for. The IAEA therefore determined that the best option was to introduce an allowance permitting each member state to multilaterally approve specified material as fissile excepted.

Purpose of the application

To increase the permissible quantity of fissile nuclides in an Industrial Package or Type B(U) package

Radioactive wastes in the UK are being packaged now for future transport to a geological disposal facility. A small proportion of the UK's higher activity waste is planned to be packaged as LSA-II material in Industrial Packages. The remainder is planned to be packaged in inner containers for future transport in Type B outer packaging. The need for Type B packages to withstand accident conditions results in a step change in design requirements and constrains the maximum payload (current UK Industrial Packages designs are up to 20 m^3, whilst current Type B packages are up to 3 m^3). Thus the need to transport wastes in Type B packages can result in increased health and safety impacts (more size reduction of wastes, more shipments - hence more package miles and greater conventional risk), greater environmental impact (more shipments, increased use of materials) and cost (more costly packaging, more packages required, increased approval burden).

Packaging of wastes in an Industrial Package has historically constrained the fissile nuclide content to the standard allowances defined in the IAEA Transport Regulations. The most notable allowance in the 2012 edition is up to 45 grams of fissile nuclides per conveyance. This limit can be very constraining for large payload containers. A fissile exception based upon mass concentration could result in a significant increase in the permissible fissile nuclide mass[2]. This would permit some wastes, that may otherwise be suitable for transport in an Industrial Package but that are assigned to be packaged in Type B(U/M)F packaging owing to their fissile nuclide content, to be reassigned to be packaged in an Industrial Package.

Some wastes in the UK are proposed to be packaged in Type B(U) packages. Like Industrial Packages, Type B(U) packages are subject to the standard fissile nuclide allowances defined in the IAEA Transport Regulations. A fissile exception based upon mass concentration could also be applied to these packages, increasing their permissible fissile nuclide content, without the need for multilateral approval of each package design to contain fissile material.

To reduce the criticality compliance assurance burden

Waste materials are often subject to uncertainty in the amount and/or disposition of their fissile nuclide content. This uncertainty must be addressed by the criticality compliance assurance

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[2] More than a factor of 400 increase for a package with a payload of 20 m^3, a density of 2 000 kgm^{-3} and applying the US CFR mass concentration of 1 gram of fissile nuclides per 2 kg of non-fissile material.

methodology such that, when taking account of uncertainty, the waste package fissile nuclide loading is demonstrably below the safe fissile mass. Where a safe fissile mass of a large payload package is defined by the standard allowances of the IAEA Transport Regulations (for instance the 45 gram allowance) this can result in onerous compliance assurance requirements. Hence increases in the permissible fissile nuclide content can also impact wastes containing small quantities of fissile nuclides through reducing the criticality compliance assurance burden.

To establish an approach to fissile exception approval in the UK

There is a great variety of waste types and properties. It is not anticipated to be practicable to produce a single application that covers all wastes that may be a candidate for fissile exception approval. Nevertheless an initial fissile exception approval will help establish an approach to approval of material as fissile excepted in the UK. That approach will be of advantage to any future material specific fissile exception applications that follow.

Approach

The approach taken by RWM in producing the application has been to justify the safety of a high-level specification that covers as broad a range of low heat generating wastes as possible. Hence rather than being specific to a particular waste type, the fissile exception is based upon generic requirements that could be met by a range of waste types and by a range of waste packaging approaches.

The technical approach is an evolution of the US CFR fissile exception which defines a mass ratio of fissile nuclides to non-fissile material that is safely subcritical in routine, normal and accident conditions of transport. In developing the fissile exception the discussions of the IAEA member states on the US CFR fissile exception were taken into account. The Office for Nuclear Regulation (ONR) has issued draft guidance to assessors to industry for comment [7] and that guidance has also been considered. In addition, the IAEA provide guidance [9] on the application of the new provisions. Much of the IAEA discussion concerned the extent to which a "risk informed" approach should be applied. Hence much of the justification of the fissile exception application is given over to the selection and justification of appropriate assumptions.

Contents of the application

The format of the fissile exception application has been derived from the DETR applicant's guide [8] taking account of IAEA guidance [9] and draft ONR guidance [7]. The applicant's guide is produced by the UK Competent Authority; its purpose is to ensure consistent presentation of all the information relevant to each application as required by the Competent Authority to enable it to carry out an assessment. The applicant's guide has not as yet been updated to reflect the changes in the 2012 edition of the IAEA Transport Regulations and therefore some adaptation was found to be necessary. The resulting format is analogous to that for special form radioactive material and is split into four main sections: Introduction, Administrative Information, Specification, and Demonstration of Regulatory Compliance. The content of the Demonstration of Regulatory Compliance section is itself adapted from the requirements for Additional Design Information Required for Fissile Material.

The specification and an overview of demonstration of regulatory compliance are provided below.

Specification

The specification defines the material that is fissile excepted. The primary audience for the specification is the user of the application, i.e. a waste packager or consignor intending to package or ship material in accordance with the approval. It is as follows:

> "*Fissile nuclides distributed throughout solid non-fissile material, provided that the mass of fissile nuclides distributed within each 280 kg mass of contiguous non-fissile material is less than 140 g for uranium-235 or 112g for plutonium or uranium-233. For materials containing a mixture of fissile nuclides these limits may be applied as a mass weighted average.*
>
> *Lead, beryllium, zirconium, bismuth, magnesium and their compounds, graphite, hydrogenous material enriched in deuterium, combustible materials and leachable materials may be present in the material but must not be included in determining the mass of solid non-fissile material.*
>
> *Plutonium may be of any isotopic composition provided that the amount of plutonium-241 is less than that of plutonium-240.*"

Definitions to ensure that the specification is unambiguous are provided. These are:

Contiguous material	shall mean a continuous portion of material. Contiguous material should be split into notional portions for assessment. The boundary of a notional portion should not be contrived to divide a localised concentration of fissile nuclides. If a notional portion has a non-fissile mass less than 280kg, the fissile nuclide limit should be reduced in proportion to the reduction in non-fissile mass.
Combustible material	shall mean material in a solid form capable of sustaining combustion either on its own or in a fire.
Fissile nuclides	shall mean uranium-233, uranium-235, plutonium-239 and plutonium-241.
Leachable material	shall mean material that is sufficiently soluble to undergo significant migration when exposed to conditions such as immersion in water.

Demonstration of Regulatory Compliance

The demonstration of regulatory compliance provides the justification of why material conforming to the specification is safely subcritical in routine, normal and accident conditions of transport. The audience for the demonstration is the Competent Authority. The demonstration must only rely upon properties that are controlled by the specification or that derive from a "risk-informed" consideration of credible worst-case scenarios.

The basic justification is that the non-fissile material will act as a parasitic absorber of neutrons and have the overall effect of reducing the number of neutrons available for fission to below the point where the fissile nuclides can maintain a self-sustaining fission chain reaction. In order to justify that the material is safe without accumulation control the demonstration presents the results of calculations for infinite seas of material. It presents calculations addressing the sensitivity to localised increases in concentration and identifies a heterogeneity limit. Finally it specifies controls to ensure the material remains safely subcritical when exposed to routine, normal and accident conditions of transport.

Mass ratio

The subcritical mass ratio for a material depends on its neutronic characteristics. It is recognised that some materials have minimal neutron absorption properties and therefore would require an impracticably low concentration of fissile nuclides to ensure subcriticality. The approach taken is to select a benchmark material to set a safe mass ratio. Materials with greater neutron absorption properties are bounded by the benchmark material, whilst materials with lesser neutron absorption properties must not be counted amongst the mass of non-fissile material (although they could be present alongside qualifying non-fissile materials).

The materials considered by the calculations are necessarily simplified compared with the wide variety of materials that could be shipped under the application. The materials that have been assessed have been chosen because they exhibit particular characteristics, these are:

- The fissile nuclides uranium-235 and plutonium-239 (where plutonium-239 is considered to bound uranium-233 and plutonium-241, so long as the amount of plutonium-241 is less than that of plutonium-240).
- Effective neutron moderators (water or polythene).
- Weak neutron absorbers, effective neutron scatterers (bismuth, allotropic carbon, beryllium, beryllium oxide, deuterium oxide, lead and magnesium compounds).
- Materials that are potentially prevalent in waste (e.g. silicon dioxide, calcium carbonate, soil, iron, aluminium, phosphorous, zirconium). These materials were selected as they exhibit intermediate properties that are representative of many waste materials i.e. they are neither

good neutron absorbers, scatterers nor moderators. Uranium-238 was also examined in this group.

Silicon dioxide was selected as the benchmark material for defining the safe mass ratio due to its high prevalence (e.g. it is a major constituent of sand, cement and soil) and as it has relatively low neutron absorption properties and so bounds most common materials. Silicon dioxide is shown to be safely subcritical for uranium-235 at a mass ratio of 1:2000 and for plutonium-239 at a mass ratio of 1:2500 and these values were selected as the concentration limits for the application. Of the other potentially prevalent waste materials considered, calcium carbonate, soil, iron, aluminium, phosphorous, and uranium-238 are bounded by silicon dioxide and can be safely included in the non-fissile mass, however zirconium exhibited atypical behaviour as described below.

Certain materials have a relatively insignificant effect on the reactivity of the system due to their low neutron absorbing properties. These materials are compounds of bismuth, beryllium, deuterium, lead and magnesium, and allotropic carbon. Whilst it would be safe for these to be in the material, their presence must not be counted when determining the non-fissile mass.

The presence of an effective moderator (e.g. water, polythene) in the material generally reduces reactivity as the dominant effect is additional neutron absorption. This trend is true for silicon dioxide and other non-fissile materials for which the k-effective[3] is relatively high (> 0.6) for the dry mixture. Other non-fissile materials (e.g. iron or aluminium) show a small initial increase in k-effective at low hydrogen concentrations until the trend of reducing reactivity asserts itself. However, the material remains safely subcritical at all concentrations. Indeed the hydrogenous moderating materials are at least as effective as silicon dioxide in maintaining subcriticality and could be safely included in the non-fissile mass if their maintained presence can be guaranteed. The exception to this is zirconium which exhibits an atypical trend of increased reactivity when certain other materials are also present. For example, a dry mixture of zirconium and plutonium-239 in the mass ratio 2500:1 is safely subcritical; when deuterium oxide is added to the mixture there is a significant increase in reactivity approaching criticality. This is attributed to zirconium's much larger and more complex neutron absorption and scattering cross sections in the intermediate neutron energy region than comparable elements such as aluminium, magnesium and silicon. This effect was not fully investigated in this work. For this reason zirconium must also be excluded in determination of the non-fissile mass.

Heterogeneity

The mass ratio limits of 1:2000 for uranium-235 and 1:2500 for plutonium-239 are defined for

[3] The k-effective is the neutron multiplication factor. A system with a k-effective less than unity is subcritical.

homogenous mixtures. Real materials will be subject to heterogeneity and this will affect the material's reactivity. To explore the effect of the heterogeneity, calculations were performed on two representative models:

1. As a regular array of spheres of the fissile nuclide within a 'sea' of the non-fissile material.
2. As a regular array of spheres of the non-fissile material each surrounded by a shell of a mixture of the fissile nuclide in water.

The overall trend was that at small radii the reactivity is practically the same as the homogeneous mixture. At large radii (e.g. 1 to 3 cm) the reactivity is being driven by the individual regions of fissile material which are largely neutronically isolated from each other. The trend in between these extremes is an initial reduction in reactivity at small particle sizes until the radius increases to a value dependent upon the non-fissile material, at which point reactivity reaches a minimum and thereafter it increases. The reactivity of homogenous silicon dioxide remains bounding of the other non-fissile materials at each sphere size. Hence the demonstration justifies that heterogeneity (i.e. regular discontinuities in the material such as latticing) is acceptable so long as the localised accumulation of fissile nuclides does not in itself exceed a safely sub-critical mass.

It is therefore necessary to establish a control on the accumulation of fissile nuclides in a region such that unsafe localised accumulations are prohibited. In order to do so the maximum mass of fissile nuclides permitted in a region of non-fissile material is compared to the subcritical spherical mass of fissile nuclides when moderated and reflected by water. It is argued that provided that the amount of fissile nuclides in each region does not exceed that mass, then the material will be safely subcritical. It is then conservatively assumed that the fissile nuclides from four such adjacent regions of material could, by chance, accumulate to form a sphere. Thus a limit is set on the maximum mass of fissile nuclides in any region of one quarter of the safely subcritical spherical mass. This logic results in the heterogeneity requirement that "the mass of fissile nuclides distributed within each 280 kg of contiguous material is less than 140 g for uranium-235 or 112g for plutonium or uranium-233", i.e. where 140 grams and 112 grams are less than one quarter of the safely sub-critical spherical mass of fully water reflected and optimally water moderated uranium-235 and plutonium-239, respectively.

Stability

The material must remain safely subcritical in routine, normal and accident conditions of transport. In order to do so the mass ratio of fissile nuclides to non-fissile material must be maintained and increases in localised concentration must be restricted. The requirements that the non-fissile material must be solid and that combustible and leachable material must not be included in determining the required mass of solid non-fissile material ensures that there would be no credible mechanism for preferential separation of the fissile nuclides and non-fissile material. The heterogeneity limit ensures that the fissile nuclides are well distributed throughout the non-fissile material and that, in the absence of a preferential mechanism for separation, the material will remain safely subcritical irrespective of mechanical rearrangement.

Applicability of the application to waste materials

Some UK waste materials presently defined as fissile material will already meet the requirements of the application, whilst others might need to be processed in order to provide the requisite properties. However such processing may have other detrimental impacts and the merits of processing the waste would need to be considered on a case-by-case basis. A description of how the requirements of the application are likely to impact the applicable wastes is as follows.

The limits on the average concentration of fissile nuclides may restrict applicability of the application for some wastes with very high fissile nuclide loadings, for instance fuel bearing wastes, or to waste materials that do not provide sufficient neutron absorption, for instance contaminated graphite. Nevertheless, limits on the average fissile nuclide concentrations are likely to cover the vast majority of UK low and intermediate level waste.

Limits on heterogeneity are likely to impact different wastes to differing extents. Wastes that are intimately mixed with fissile nuclides, such as sludges, resins, raffinates or flocculants, are likely to intrinsically meet any heterogeneity limits and are ideal candidates for fissile exception. Wastes that are mixed to a lesser extent such as miscellaneous contaminated items, plutonium contaminated materials or contaminated filters, sand, gravel or soil are also good candidates. Whilst these materials will be subject to a greater variation in the disposition of the fissile nuclides, significant localised concentrations (i.e. lumps that are a sizeable fraction of a minimum subcritical mass) are unlikely to be possible. Hence the criticality compliance assurance method would need to allow for uncertainty in the concentration of fissile nuclides material, but accumulation of fissile nuclides into an unsafe mass is unlikely to be of concern. Other wastes include significant localised concentrations of fissile nuclides, for instance fuel element debris, fuel hulls or end cropping's or post-irradiation examination fuel samples. These wastes are likely to pose the greatest challenge to meeting the requirements for fissile exception. Where the maximum fissile nuclide lump size is sufficiently small it may be possible to make a probabilistic compliance assurance argument that the likelihood of an unsafe accumulation is acceptably low. Alternatively, treatment may be necessary to reduce the degree of heterogeneity, for instance through dissolution or shredding of the waste, if this is practicable and economic.

Limits to ensure that changes in disposition of fissile nuclides during routine, normal and accident conditions do not compromise criticality safety may require treatment of the waste to ensure that the fissile nuclides and non-fissile material are not preferentially separable. For instance preferential separation by vibration of fissile nuclide contaminated materials could be mitigated by fixing contamination in place (e.g. the capping of pipes, surface preparation or encapsulation), whilst the preferential separation of non-fissile materials when immersed in fire or water could be mitigated by the removal of liquids, chemical conditioning or encapsulation. Again such measures would need to be practicable and economic.

In order to minimise the complexity of the application it has focussed on bounding specifications of pure uranium-235 or plutonium-239. Higher fissile nuclide mass concentrations could be demonstrated to be safe if credit were taken for the potential presence of other isotopies of uranium or plutonium. Furthermore the fissile exception application has excluded some materials from being counted amongst the safe fissile mass that are known to be major components of some UK wastes, for instance graphite, zirconium and magnesium compounds. As a result the application will not cover all UK waste materials that are potential candidates for fissile exception approval. Waste specific applications could be developed for these wastes using the same overall approach as the RWM application, adapted to take account of the specific properties of the waste.

Competent Authority response

The application [2] was submitted to the UK Competent Authority in 2015. Their response has been largely positive but has included a number of technical questions, a few of which will require some extension of the criticality calculations. These questions concern the sensitivity to: localised regions of higher fissile concentration; temperature changes; and code validation. RWM intend to progress this work later this year.

Conclusions

The 2012 edition of the IAEA Transport Regulations introduces a provision permitting a Competent Authority to approve material as fissile excepted. Many waste materials are potential candidates for fissile excepted approval. RWM has identified that there is an opportunity to gain approval of a generic fissile exception. Working in conjunction with International Nuclear Services and Sellafield Ltd an application has been produced. This paper describes the approach taken in the development of that fissile exception application.

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