Exemption, exception and other criteria for transport criticality safety

Dennis Mennerdahl

E Mennerdahl Systems, Täby, SE

Summary

Many strange concepts, requirements and specifications related to criticality safety are present in the Regulations [1]. Some earlier problems have been corrected but, going back to 1961 and the first edition of the Regulations, [11] it seems as many changes have been to the worse. Fissile material was defined correctly as a material that could consist of or contain fissile nuclides. Materials consisting of pure fissile nuclides don't exist but are important in package designs. ^{238}Pu was included as a fissile nuclide only as an emergency, because there was no alternative, but this caused some people to think that all nuclides supporting criticality are fissile. Neutron interaction between different (non-identical) packages had to be evaluated, making the transport index or allowable number of packages a credible safety control. That is not true anymore. The 15 gram exception limit for fissile nuclides was combined with a transport mode limit, similar to but more restrictive than the current consignment limit.

The confinement system was introduced to help with formulation of a single requirement for safety of the containment system but is becoming something very different. Controls before the first use of a packaging have become controls of the first use of a package, supporting multiple shipments of the same package.

The lack of exemption limits for fissile material essentially makes all radioactive materials fissile (all radioactive material contains some fissile atoms). Radioactive material seems to be defined without consideration of the criticality hazard of the material. LSA materials are defined with consideration of criticality, but only relates to quantities in fissile exceptions when other properties can be equally or more important.

In July 2004, a number of proposals to IAEA have been submitted by Sweden [2] to improve and expand the criticality safety control of the Regulations. Essential is the introduction of the fissionable nuclide and material concepts in addition to revised definitions of fissile nuclides and materials. Introduction of fissionable exemption (total exclusion as opposed to exception) limits is also essential. These definitions and exemption limits can be structured in a similar way as those for radioactive material. The problems caused by retaining the current definition of fissile material are pointed out in the proposals.

To make the Regulations more realistic and the requirements more consistent with each other, it is proposed that the total number of packages with fissionable materials in a group or consignment is limited to 500. This will make it possible to round the CSI down to zero and will simplify determination of safe but realistic fissionable exemption and exception types. Consignment mass limits for fissionable exceptions are essential whenever human error or accident conditions can cause a criticality hazard.

Shipment approval is already used to allow larger quantities of packages with fissile material (total CSI of 100) and can be expanded to cover other needs when one or more of the general criticality safety requirements are not complied with. The 10 cm minimum dimension requirement is not always needed for criticality safety. It should be required only in para. 675 and for one exception type in para. 672. Air shipments of low-enriched uranium cannot lead to a fast criticality accident and can be exempted from para. 680. The confinement system concept should be removed and replaced with a similar requirement as that in previous Regulations.

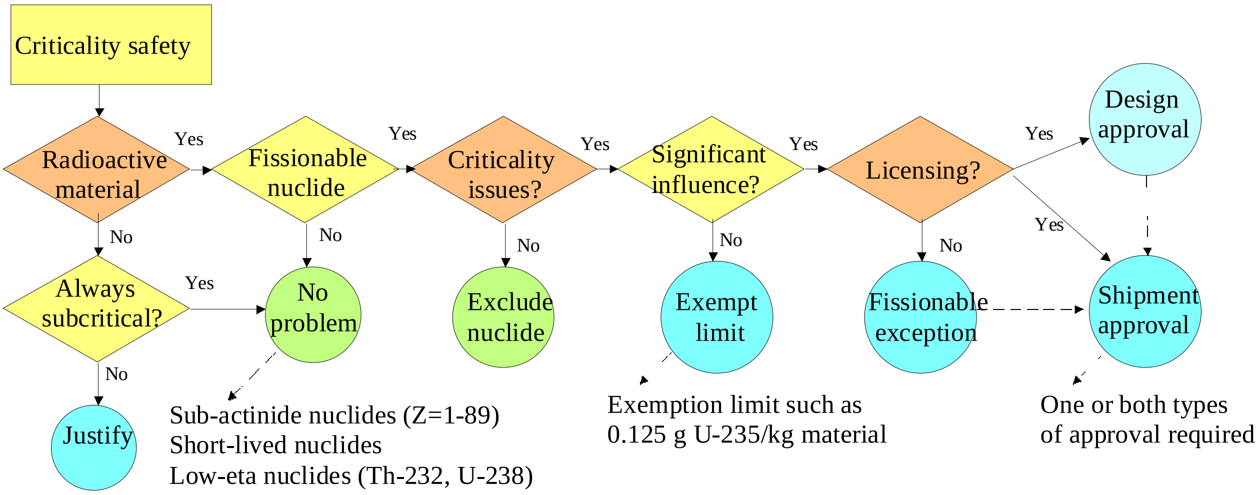
1. Background with some essential concepts

Some concepts that are essential for this paper are described here as a background; e*xemption*, *exception*, *fissionable*, *fissile*, *normal,* and *accident conditions of transport. Regulations* refer to the IAEA Transport Regulations for Radioactive Material in general. If a special edition is intended, it will be referenced.

Exemption means exclusion. An exempted radioactive, fissionable or fissile nuclide is non-radioactive, non-fissionable or non-fissile respectively. *Exception* means relaxation of some requirements under certain conditions. An excepted radioactive, fissionable or fissile nuclide is still radioactive, fissionable or fissile respectively. Similar concepts as for nuclides apply to materials, packages and consignments.

Fissionable and *fissile* are defined in international and national glossaries and standards [3-6]. A *fissionable nuclide* can be fissioned by a free neutron. A *fissionable material* contains such nuclides. A *fissile nuclide* can support criticality with slow neutrons. This support can be direct in a mixture of the fissile nuclide and a moderator. The support can also be indirect, where an initially sub-critical mixture of another fissile nuclide and a moderator can be driven critical by additional fissions caused by slow neutrons in the nuclide under evaluation. Radioactive decay can produce more hazardous fissionable and fissile nuclides. Radioactive decay can reduce the neutron absorbing effects of some components in a fissionable material, thus increasing its criticality safety hazard. In the Regulations, the selection of fissionable and fissile nuclides as well as materials can be limited to those that could be a criticality safety problem during normal and accident conditions of transport. Human error before, during and after the shipment also needs to be considered.

Normal conditions of transport for a package mean postulated test conditions that are intended to cover common incidents during handling, shipment and storage. For individual packages under normal conditions, the requirements also cover human error leading to water in- or out-leakage. For a configuration of normal condition packages, human error is also considered; not due to water in- or out-leakage but due to multiple loadings by a factor of 5. *Accident conditions of transport* for a package mean postulated test conditions that are intended to cover severe accidents during handling, shipment and storage. Human error is considered in a similar way as for normal condition packages except that the multiple loading is limited to a factor 2. Smaller factors are accepted under certain conditions; one being the requirement for multilateral shipment approval.



2. Criticality during transport

Criticality in any form during transport of fissionable material is unacceptable (nuclear reactor-driven transport vehicles or equipment not included), even when nobody is expected to get hurt. The major reasons are that criticality accidents in nuclear facilities have caused several fatalities, that similar physics reactions could happen during transport and that it is difficult to predict what could happen in a random criticality accident during transport. Unlike in most nuclear facilities, transport can involve operations with fissionable material very close to the public.

The reactions to the JCO criticality accident in Japan in 1999 show how unacceptable a transport criticality accident could be. The root cause of the JCO accident was the formal statements in 1984 by management and competent authorities of a criticality accident as being incredible. Not long before, in 1981, a transport criticality safety technical committee meeting [7] organized by IAEA concluded that criticality during transport was incredible. Each conclusion, IAEA in 1981 and Japan in 1984, in itself increased the potential for and the consequences of a criticality accident by several orders of magnitude. The uranyl nitrate solution at the JCO facility was being prepared for transport. All of the fissile material could easily have been shipped in excepted packages and in a volume smaller than any authority approved package design would allow. Many research reactors around the world use similar fissile material.

The health consequences of a criticality accident due to maximum accident conditions of transport will probably not be significantly more severe than the consequences of the transport accident in itself. Political and economical consequences will probably not be as dramatic as if the criticality accident is caused by human error alone. Human error in design, evaluation, fabrication, maintenance and preparation for shipment as well as during shipment needs to be considered. The history of criticality safety shows that the accidents have occurred due to human error. The political and economical consequences of criticality accidents in facilities that are understood by the public, authorities, management and operators to involve a criticality hazard have been relatively small. The JCO accident is an exception since it could not happen. A criticality accident during transport due to human error will probably also cause enormous political and economical damage since the specialists have concluded that it cannot happen.

An essential requirement to reduce the potential for human error is to have regulations that are clear, correct, complete, and understood.

3. Protection against radioactivity (shielding, contamination and heat) versus criticality

Radioactivity is an existing property of a nuclide, including potential future decay chains. The radioactive hazard of the nuclide depends on types of radioactivity, energy levels and decay times as well as the chemical and physical forms of the material it is positioned in. Criticality generates radioactivity but is not caused by it. Criticality safety prevents radioactivity in the future. The criticality hazard of the nuclide depends on its fission sensitivity to free neutrons of different energies, the fission process (numbers and energies of produced neutrons) and the properties and geometry forms of the material it is located in as well as those of surrounding materials.

Requirements for shielding are caused by direct radiation from the radioactive source. Containment is required to restrict contamination of the environment (including people). Radiation that is not harmful inside a package can be dangerous in escaped materials. Heat generation from radiation can be a safety problem during transport.

Protection against the occurrence of criticality is not related to radiation protection. Direct radiation from a material or package is not in itself related to the criticality hazard (unless criticality has occurred and unless the radiation or lack of radiation can be used to verify the contents of the package). Containment can be used to reduce the potential for criticality, but it is not the radiation properties of the escaped materials that determine the criticality requirements on containment. Loss of non-radioactive components of the contents or the packaging may be more hazardous to criticality safety than loss of some of the radioactive material.

The clear distinction between radiation protection and criticality safety is vital to create clear, correct and complete Regulations and to assure safety during transport of radioactive materials.

4. Exemption limits for radioactive materials considering radioactivity and criticality

The Regulations [1] define radioactive material based on the total specific activity of the material and the total activity of the consignment. Section IV specifies the exemption limits for each nuclide and how to determine the limits for mixtures. For criticality safety, the most interesting nuclide is ^{235}U with its low specific activity and small minimum critical mass. Other fissile nuclides have smaller minimum critical masses [8, 9] but their specific activities are much higher, giving the highest neutron multiplication factor k_{eff} for the ^{235}U exemption limit

The specific activity exemption limit for ^{235}U is 10 Bq/g of material. This corresponds to a concentration of 0.125 g of ^{235}U per kg of material. This is sufficient to support criticality in mixtures between ^{235}U and one or more of the special moderators deuterium, graphite and beryllium oxide [2]. Previous editions of the Regulations had an exemption limit of 70 Bq/g or 0.875 g/kg.

The minimum critical volume with a mixture of ^{235}U and heavy water or graphite is smaller than a large freight container even if the mixture is a non-radioactive material (less than 10 Bq/g). It seems as if the criticality hazard was not considered when the exemption limits were determined. Is it reasonable to exempt a material that can support criticality? Did anybody evaluate the likelihood of a large volume of a pure mixture of ^{235}U and the mentioned moderators? Emergency reactions to this type of shipment lead to revised national regulations [10]. Presence of other radionuclides reduces the ^{235}U exemption limit significantly.

For clarity and to avoid future mistakes, it is important to include the criticality hazard in the definition of radioactive material in the Regulations [1, 2]. It is considered for the special case of Low Specific Activity (LSA) material.

5. Current definition and (ab)use of the fissile material concept in the Regulations

The definition of fissile material in the Regulations [1] seems to be an unsuccessful attempt of combining good but incompatible ideas. This causes difficulties in applying the definition and in improving the Regulations [1].

A "good" idea is to use the concept of *fissile material* as identical to that of *fissile nuclides*. A material containing different fissile nuclides could be summed in one quantity, sometimes after giving different weights to each fissile nuclide. This material will not be a real material but can be the basis for a package design. A second good idea is to use fissile material as everybody else in the world would use such a concept; a real material that can be produced, seen, handled and transported.

A third "good" idea is to use the fissile concept for any nuclide that could support criticality. This conflicts with the established definition of fissile which relates to criticality with slow neutrons. The non-fissile nuclide ^{238}Pu has been included in the list of fissile nuclides, but it was for practical reasons. ^{238}Pu can support criticality and since there was no definition and no restrictions related to transport of fissionable nuclides and materials, it was included as fissile. In the revision process leading to the current Regulations [1], ^{238}Pu was removed from the definition of fissile material because it is not fissile. There was no other definition to use so it was simply dropped. During later revision processes, several member states (France, U.K. and U.S.) have proposed not only additional fissile nuclides but also non-fissile nuclides such as ^{238}Pu. A better solution is described in the next section.

The current definition [1] is quoted below, with some irrelevant text over-stricken.

> "222. *Fissile material* shall mean uranium-233, uranium-235, plutonium-239, plutonium-241, or any combination of these radionuclides. ~~Excepted from this definition is:~~
>
> ~~(a) *natural uranium* or *depleted uranium* which is unirradiated, and~~
> ~~(b) *natural uranium* or *depleted uranium* which has been irradiated in thermal reactors only."~~

The definition only applies to the listed fissile nuclides. A material that contains but does not consist purely of these nuclides is not fissile. Enriched, natural and depleted uranium are not defined as fissile materials. The materials in the over-stricken text don't give exceptions to the definition since they are not covered by the definition.

The first edition of the Regulations [11] included a correct definition. Fissile material consisted of the mentioned nuclides or any material containing those nuclides. That allows for a material consisting of pure fissile nuclides.

6. New fissile material definition: Supported by member states, rejected by IAEA – Why?

In 2002, Sweden proposed a correction of the definition to replace the current fissile material with fissile nuclides and to support the use of fissile material as a material containing fissile nuclides. The 2002 and 2003 IAEA review panels supported this change, after some modification. The 120 day IAEA member states review did not result in any serious opposition. During the final preparation for the new edition of the Regulations, the 2004 TRANSCC meting rejected the proposal. The exact reason is not known to the author at the time of writing this paper. However, it seems as if a problem or discussion related to a separate issue that is not related to changing the definition of fissile material caused TRANSCC to reject the proposal. Clarifying or postponing was not an option.

The issue causing confusion seems to be whether fissile nuclides in natural and depleted uranium should be accounted for to control the quantity of fissile nuclides. The current definition [1] does not say anything about this; all fissile nuclides must be accounted for. However, many people read the intention of the current definition as if fissile nuclides in natural and depleted uranium shipped separately from other fissile materials can be exempted from the criticality safety requirements of the Regulations [1]. This intention was clearly included in the proposed definition and accepted by the member states after the review panels and the 120 day review period.

The consequential changes to other paragraphs seem clear and without problems related to the definition change. Other problems were discovered during the revision process, including discussions on what the current text means and how it is applied. They should be dealt with separately, independent of the fissile material definition. Proposals are sometimes rejected during the revision process since they need adjustments that go outside the scope of the original proposal. This time, the final rejection seems to be based on the opposite case; the proposal did not solve all the other problems with the Regulations.

For the next review period Sweden has submitted several proposals [2] related to the definition of fissile material. To stress that the current flawed definition causes many problems, three different interpretations have been proposed. A fourth definition is essentially identical to the one that was approved by the 2002 and 2003 review panels (after consideration of comments from the 120-day member state review period). The fifth proposal, the one that should be preferred, includes the definition of fissionable nuclides and materials. Several other proposals related to criticality safety build on this one. It is described in the next section.

7. Fissionable nuclides and materials

The non-fissile nuclide ^{238}Pu has been available in significant quantities for many years. It is used as a heat source but also supports criticality. The strong heat generation prevents a credible accumulation of a critical mass that is supported primarily by ^{238}Pu during transport. In mixtures with other fissionable and/or fissile nuclides, presence of ^{238}Pu could make an otherwise sub-critical system critical. In some irradiated fuels, the presence of curium (combined effect of all isotopes) has a positive effect on k_{eff}. Recently, there have been critical experiments where a significant fraction of the critical mass has consisted of the non-fissile nuclide neptunium-237. Transmutation of waste actinides could lead to new criticality safety challenges.

All plutonium isotopes are fissionable and support criticality but only some of them are fissile. In criticality safety reports and in authority approval certificates involving plutonium, its isotopic composition is often specified due to the importance to criticality safety. Often, there is a restriction limiting the fissile plutonium isotopes contents to some fraction of the total plutonium contents. The fissile property of some fissionable nuclides can be used to improve the Regulations in addition to being used in safety reports and authority approvals.

Both the *fissionable* and the *fissile* concepts are useful and needed in future Regulations. Their general definitions [3-6] are well established and used in scientific, engineering and safety related studies, guides and standards. A Swedish proposal to introduce the *fissionable* concept formally in the Regulations in addition to a changed definition of the *fissile* concept has been prepared for the next revision cycle [2].

There are many fissionable nuclides, currently not covered by the Regulations [1], that can support criticality and some of them may need to be transported in the near future due to new technical and political developments. There are several advantages in introducing the fissionable concept soon. There is plenty of time to prepare requirements that are efficient and safe for the non-fissile but fissionable nuclides. In particular, the exemption and exception limits can be determined using different criteria than for fissile nuclides. The advantages of carrying out critical experiments to obtain more accurate data for the fissionable nuclides, and thus reducing the uncertainties, can easier be compared with the costs. New package designs require large budgets and long preparations to get evaluated, tested and approved. A stable and predictable expansion and improvement of the Regulations will simplify the development of new package designs.

The European Commission in 2002 supported a study [8, 9] by participants from France, UK and Sweden on criticality safety during transport of actinides. Nuclide properties, exception limits and other issues were covered. It is important to determine the criteria before the limits are established. New and improved data, including results from critical experiments were obtained from outside sources during the study. If the IAEA review panels support inclusion of some of these nuclides, the actual limits should be determined with consideration of the most recent data and experiments.

8. Criticality safety structure of the Regulations.

Criticality safety during transport is one of the main objectives of the Regulations [1]. The chart on the first page of this paper gives a structural approach to criticality safety during transport. The following issues need to be covered:

- Selection of nuclides that can support criticality and could be transported in the near future
- Criteria for exemption of materials, packages and consignments from criticality safety control
- Exemption limits for selected materials based on the established criteria
- Criteria for exception of materials, packages and consignments from specified requirements
- Exception limits for various materials, packages and consignments
- Package design criteria to support criticality safety during transport
- Packaging quality assurance, contents verification and loading controls

- Shipment controls to assure criticality safety during transport
- Evaluation reports demonstrating that a package design or shipment complies with the safety criteria
- Authority documents showing that a package design or shipment complies with the safety criteria

Some of the existing criteria for exemption, exception and package designs can be derived from IAEA meeting working papers, published documentation or by logic. Some of the criteria are difficult to motivate and their derivation may need access to working documents or information from participants at previous review panels, sometimes going back to 1960 [11, 12]. New and revised criteria are needed to account for new developments and needs, to make the requirements clearer and more consistent with each other as well as to correct mistakes [2].

New exceptions for fissile materials, packages and consignments should not be introduced until the criticality safety structure of the Regulations is improved and the existing requirements are consistent with each other.

9. Criticality and radioactivity related specification of nuclides and materials in Section IV

The definition of radioactive material is based on the material activity (radioactivity). The actual radioactive nuclide selection and associated limits are given in Section IV of the Regulations [1]. Exemption limits are given to allow specification of non-radioactive materials. The definition of fissile material is not acceptable.

It is now a good time to introduce fissionable nuclides and materials in the Regulations [2]. The definition should describe the physics properties of such nuclides and materials with future transport applications in perspective. The selection of nuclides and materials as well as exemption limits should be given in Section IV in a similar way as for radioactive materials. The fissile property is very important and should be specified when applicable.

It is important that the exemption limits are complied with also under accident conditions and considering human error. E.g. sedimentation may increase the specific activity by a factor of 10 or more but also reduces the volume. The radiological consequences are predictable and probably not very serious. The same increase in the fissile concentration may cause criticality, going from essentially zero to infinite neutron multiplication.

Very large quantities of mixtures of the special moderators with other fissile nuclides than ^{235}U are more unlikely. The fissionable exemption concentration limit for materials containing ^{235}U should be maintained at 0.125 g ^{235}U per kg material or reduced. Since the radioactive material exemption limit is the same, it will be difficult to reduce the limit. For materials containing other fissionable nuclides, the fissionable exemption limits will be much higher than the radioactive exemption limits. The limits for other fissile nuclides can be determined using ^{235}U as a basis. Other criteria could be used for non-fissile fissionable nuclides.

Large safety factors should be used for fissionable nuclides for which nuclear cross sections and other data are not validated through evaluation of experiments. When better data become available, the safety factors can be reduced. Since the limits will be relaxed, no problems with existing applications are expected.

Mixtures of fissionable nuclides need special consideration. Summing the fractions of the current mass to the limit for each nuclide is sometimes called the Rule Of Fractions (ROF). For some mixtures, the critical masses are smaller than the ROF predicts. This problem could be dealt with in several ways. One way is to reduce the limits for less important nuclides while keeping the best estimate limits for important and established nuclides such as ^{235}U and ^{239}Pu. Whatever method is used to solve the problem with mixtures of fissionable nuclides; it needs to be validated. Some mixtures are caused by irradiation and radioactive decay. A non-fissile nuclide such as ^{233}Pa decays into the fissile nuclide ^{233}U and needs consideration if transported short after irradiation.

The table is proposed [2] to be added to Section IV of the Regulations. The actual limits are not included since they depend on the criteria to be used. Critical mass data and infinite multiplication factors have been calculated and the use of factors to obtain safe limits have been published separately [8, 9]. Those limits are exception limits equivalent to the 15 g package limit for ^{235}U. The table should not contain the exception limits but rather the exemption limits, as discussed previously. The methods to determine the various limits are closely connected. A difference between the table and similar tables [8, 9] is that ^{254}Cf has been classed as fissile. The reason is similar as that for calling natural uranium fissile; the net production of neutrons (eta) in a thermal spectrum is larger than 1. Unlike natural uranium, ^{254}Cf can also support criticality in a fast neutron energy spectrum. ^{233}Pa is included even though its half-life is shorter than 45 days. This time limit needs to be discussed.

Fissionable nuclide	Exemption density limit (g/cm^3)	Consignment exemption mass limit (g)	Fissile? (Y/N)
^{229}Th			N
^{231}Pa			N
^{233}Pa*			Y*
^{232}U			Y
^{233}U			Y
^{234}U			N
^{235}U			Y
^{235}Np			N
^{236}Np			Y
^{237}Np			N
^{236}Pu			Y
^{237}Pu			Y
^{238}Pu			N
^{239}Pu			Y
^{240}Pu			N
^{241}Pu			Y
^{242}Pu			N
^{244}Pu			N
^{241}Am			N
^{242m}Am			Y
^{243}Am			N
^{242}Cm			N
^{243}Cm			Y
^{244}Cm			N
^{245}Cm			Y
^{246}Cm			N
^{247}Cm			Y
^{248}Cm			N
^{250}Cm			N
^{247}Bk			Y
^{248}Bk			Y
^{249}Bk			N
^{248}Cf			N
^{249}Cf			Y
^{250}Cf			N
^{251}Cf			Y
^{252}Cf			Y
^{254}Cf			Y**
^{252}Es			Y
^{254}Es			Y
^{257}Fm			Y
^{258}Md			Y
^{261}Md			N
^{265}Md			N
^{270}No			N
^{278}Sg			N
^{282}Hs			N
^{287}110			Y
^{288}110			N

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10. Control of accumulation of packages containing fissionable materials

The concentration and mass of fissionable materials are important specifications when determining the criticality hazard. Is there any practical restriction on the maximum number of packages in a consignment or in a group of packages? The limit should be based on the number of packages in itself, not on the properties of each package. The 1961 Regulations [11] had a number limit of 50 packages of radioactive material per mode of transport.

The Regulations [1] require that the number of packages in the criticality safety assessment should be effectively infinite to allow transport without criticality safety index (CSI) control. The advisory material [13] has the same information; the CSI cannot be rounded down to zero. These requirements relate to package designs approved by authorities. Such packages are usually large and accident-resistant.

On the other hand, IAEA meetings on criticality safety [7, 14 and 15] and review panel discussions [12] show that most criticality safety specialists did not and still don't seem to consider a few hundred excepted packages in a consignment or group of packages credible.

The author was chairing a working group on fissile exceptions at a meeting in 1981 [7]. The reason was that the author questioned the exception criteria. There was little interest from other members to change the exceptions. As a chairman having different views to the rest of the group, it was difficult to write a working group report. A non-member of the group offered to help in writing the report. He temporarily convinced the author that a bulk shipment of fissile material is the same as a bulk shipment of packages with fissile material and that the 15 gram limit applied to the consignment in both cases. This was acceptable to the author and explains the lack of proposals or explanations in the working group report of the meeting in 1981 [7].

Immediately after the 1981 meeting, the truth became clear; bulk shipment of material referred to unpackaged material only. A formal Swedish proposal [16] was later submitted to IAEA to reduce the number of packages based on the 15 g exception subpara. to 10. The proposal was rejected by the reviewers, probably with a reference to the 1981 meeting report (maybe without knowledge that the proposal was made after the meeting). A similar proposal from France was rejected by a meeting [14] in 1992. Experience from several states, in particular Belgium, convinced the review panel in 1993 that changes to the fissile exceptions were needed.

Can the number of packages in a consignment or group of packages be limited as a general case? If 500 is used as the limit for authorized packages in a group without shipment approval, it means that the CSI can be set to zero e.g. if the number "N" is 1000 (half or less of the CSI of 0.1). 2000 damaged condition packages and 5000 normal condition packages must be sub-critical. The total limit to 500 packages per group would normally lead to a much lower total CSI than 50. However, for the normally large and strong packages that are used for fissile material, the limit to 500 per group of packages should not be an economical or practical problem.

For exempted and excepted packages, the practical control of the total number of packages is more complicated. The total volume could be very small, in particular if the 10 cm minimum dimension for routine condition packages is not required. If the exemption or exception criteria build on the limitation of the total number of packages, that maximum number should also be a requirement. However, if an overpack complies with the package exception limit, it can be accounted for as a single package in this control.

Another accumulation control is related to the total credible volume of a group of packages. A large freight container is probably a good reference. If the total volume corresponding to five such containers under normal conditions of transport and two under accident conditions are sub-critical there should not be any need to evaluate larger configurations. This could be applied to packages complying with authorized package designs as well as to exempted and excepted packages.

It is difficult to find explanations to many of the requirements in the Regulations. Old working papers and conference papers contain valuable information but are difficult to trace. A successful effort in finding such papers [9] makes it easier to understand the development of the Regulations. A paper from 1979 [17] describes some of the ideas related to fissile exceptions that have been discussed later, including the credible maximum volumes of configurations of normal and accident condition packages discussed in this paper. There are more such important papers that should be compiled and discussed or used as background information.

Accumulation of packages can be more hazardous if additional materials to those in the packages are present. Water from the environment shall be evaluated for accident condition package configurations. Water, ice, snow, etc. shall be considered for normal and accident condition package configurations. Other materials that are or could be added to the packages before or during transport shall be evaluated if they could reduce safety.

Criticality is often driven by slow neutrons inside the packages, but neutron interaction between packages is usually dominated by fast neutrons that later may slow down inside the package. Water may reduce interaction while steel and other scattering but essentially non-moderating materials can increase interaction (reduced neutron leakage). Water is always credible, at least under accident conditions of transport. Other materials need to be considered and evaluated when credible.

11. Exception of materials, packages and consignments containing fissionable nuclides

For a material to be non-fissionable or non-fissile, exemption is required. Each exception type covers fissile material. The existing exception types are well established, even if some of them have been made more restrictive with the 1996 edition of the Regulations. Before adding new exception types, the existing types should be evaluated and structured in a format that will help in expanding the number of fissionable nuclides to be regulated as well as to keep the exception types limited [2]. Including a large number of exception types in a short time in the Regulations could be confusing, not only to the users but also to the reviewers and writers of the Regulations. A new exception type should be well established before being included in the Regulations. A mechanism to deal with immediate needs is the proposed shipping approval option [2].

The exemption limit for a material containing a certain fissionable nuclide can be used as a basis for other limits in the Regulations. E.g., the proposed [2] fissionable material exemption limit for a consignment containing ^{235}U is 0.125 g. The exception limit for a package with ^{235}U is 15 g. A factor 120 can be used to determine the package exception limit from the consignment exemption limit, not only for ^{235}U but for all fissionable nuclides. The exception consignment limits can be specified as a multiple of the exemption consignment limits.

The ROF method for dealing with mixtures of fissionable nuclides needs special consideration as discussed in the section about exemption limits. With only the four current fissile nuclides to consider, there is no problem. Further, radioactive decay before and during transport needs to be considered [8, 9].

Five different classes of exception types have been proposed [2]:

i. Material concentration or density limits. No mass or volume limits are required. Extremely large numbers of packages or volumes of package configurations or extreme human error needed for a criticality hazard.
ii. A combination of package and consignment mass limits.
iii. Concentration or density limit together with a consignment mass limit.
iv. Consignment limit for unpackaged material or for unlimited quantities of the special moderators deuterium, graphite or beryllium.
v. Shipment approval

Human error and accident conditions need to be considered. A fundamental principle is that different exception types must not be mixed in the same group of packages, unless this is specifically allowed. Excepted packages must not be mixed with authority approved packages unless this is specifically allowed in one of the exception types of the Regulations or in the competent authority design approval.

Similar principles can be applied to exemption as to exception types. The major difference is the complete lack of administrative control for exempted materials, packages and consignments. Human error motivates additional safety factors for exemptions, e.g. a factor 100, compared with those for exceptions.

11.1. Exception motivated by material properties only

Existing exception types in this class are uranium with less than 1 % ^{235}U by mass not forming a lattice and uranyl nitrate solution with uranium containing at most 2 % ^{235}U by mass. Natural and depleted uranium, not irradiated in a non-thermal reactor, are intended to be excepted from something, but the Regulations [1] are not clear on what.

It is proposed [2] that the number of packages **with fissionable material** shall be restricted to 500 in any group of packages and in any consignment. The restriction should be applied as a maximum both to excepted as well as to authority approved packages. This corresponds to a CSI of 0.1. To round the CSI down to zero, it should be less than 0.05, corresponding to a number N of 1000. Rounding down is not allowed today.

The maximum credible total volume of packages could also be used to determine reasonable exception and exemption limits. The volumes of five large freight containers of normal condition packages and two large freight containers with damaged packages may be considered as the maximum credible volume, with good reflection. It is essential that the material properties during accident conditions are considered when the limits are determined.

Natural uranium is a fissile material but cannot support criticality on its own or in a mixture with water. In a mixture with another fissile material that cannot support criticality for some reason, the combination could make criticality likely. An example is a material consisting of a mixture at a concentration of 5 g ^{241}Pu per 1 kg of hydrogen. Mixing this material with natural uranium increases the neutron multiplication factor more than either material could achieve on its own or with water. This shows that even if different exception types belong to the same class of exceptions mixing the types can cause criticality safety problems.

There are many materials that can be excepted (and many others that can be exempted). Only those that are needed frequently should be included in the Regulations. Others could be listed in the Advisory Material or established in other ways. That will simplify a quick issue of a shipment approval.

11.2. A combination of package and consignment mass limits

The 15 g exception limit for a single package is very generous but established. If the package actually contains 15 grams, a corresponding CSI would be about 2 (2N corresponds to about 50). In1961 [11] when the total number of all packages with radioactive material was limited to 50, the probability for human error was small. This is probably similar as for shipment approval today.

The limitation to 15 g per package allows for a significant human error involving a single or a few packages. If the whole consignment limit was allowed in a single package, a single human error could be sufficient for criticality. Other exception limits could be based on similar criteria as for ^{235}U. Since the consignment exemption limit is 0.125 g U-235, the package exception limit can easily be expressed as a multiple factor 120 of that limit.

The current exception type involving 1 kg of plutonium containing less than 20 % by mass of fissile plutonium has been reasonable in the past. The only significant fissile plutonium isotopes have been ^{239}Pu and ^{241}Pu. The future transport of plutonium may involve other fissile isotopes such as ^{236}Pu and ^{237}Pu. A consignment limit is not expressed in the Regulations but should be considered as a principle [2, 15, 17]. The basis for the exception type is that the heat generation of ^{238}Pu makes it impossible to ship several kg of this material in one lump without cooling and other protection, reducing the criticality hazard. There are other similar fissionable nuclides.

11.3. Material concentration or density limit together with a consignment mass limit

The consignment limit is added to account for accident conditions of transport or human error. The existing exception type for 5 g of fissile nuclides per kg of hydrogen is based on calculations of dilutions of fissile nuclides with water. The infinite neutron multiplication factor should be less than 1.000. For pure ^{241}Pu an infinite system may be just critical but this is not a problem. However, if natural uranium is added to that material, criticality is possible in quite a small volume. This is not allowed according to the current Regulations [1] but since the intentions of those Regulations are not clear, mistakes are quite likely.

The current exception type 5 g of fissile nuclides in any 10 litre volume is based on neutron leakage or a limitation of the credible volume of the material under routine conditions of transport. High concentrations of deuterium, graphite and beryllium are not allowed.

The proposals by the U.S. for new exception types based on average concentrations are difficult to specify in a general way that covers accident conditions and human error. Adding a consignment limit may be a good way to introduce these exception types. The consignment limit could be relaxed with a shipment approval [2], see below.

11.4. Consignment limit for unpackaged material or for unlimited quantities of special moderators

The current exception type with a consignment limit for 15 g of fissile nuclides for unpackaged material is reasonable. There is also a need to ship significant quantities of special moderators based on deuterium, graphite and beryllium. These may be contaminated with fissile nuclides. A 15 g consignment limit may solve some of the needs while preserving criticality safety [2].

11.5. Shipment approval for materials, package or consignments not meeting all general requirements

The current Regulations [1] allow larger consignments of packages containing fissile materials if shipment approval is obtained. The same philosophy can be applied to excepted materials, packages and consignments as well as to packages not complying with all conditions for a package design [2].

Compensating circumstances such as demonstrated measurement and control procedures of shipped materials, climate conditions (excluding very hot or very cold temperatures), etc. need to be present. Special arrangement is an available option but it is too complicated in most cases where simple and obvious solutions are available.

An example is the shipment of waste materials that does not comply with any of the exception types. Information about the quality assurance and material verification at a site before shipment could reduce the consignment limit restrictions considerably.

12. Transparency between criticality safety requirements and effects

The potential for misunderstanding of the Regulations is related to the clarity of the structure and text of the requirements. Maintenance, improvement and expansion of the Regulations are all simplified if the structure and text are easy to follow. Examples of problems are listed and briefly commented below:

- Definition of fissile material [2]. It is now identical to fissile nuclides which is not only a waste of language but is contradictory to normal use of the material concept. The definition itself is contradictory. The original text from 1961 [11] is correct and defines fissile material as the fissile nuclides or a material containing any of the fissile nuclides. This covers the case of an absolutely pure sample of a fissile nuclide. That may not be a realistic material but package designs are usually not based on real materials but on simplified models.

- Requirements before the first shipment of a package [2]. During consideration of new fissile and fissionable nuclides and materials, the issue of maximum time for a shipment became important. Radioactive decay and maybe other changes to the radioactive contents may increase the hazards during each shipment. Realising that the Regulations since 1973 or longer include a special paragraph to cover multiple shipments of the same package, the maximum length of a transport becomes complicated. The advisory material and some competent authorities have expressed the opinion that the intention is to cover the first use of a packaging, not a package. Can such a mistake survive 30 years of implementation, translation and application? What is the maximum total time for multiple shipments of a package?

- Safety of real shipments, rather than simplified configurations of identical packages [2]. The CSI is currently not a credible safety control. The first edition of the Regulations [11] required consideration of real shipments, i.e. non-identical packages. A new example of this problem will be presented later in 2004 [18].

- The *confinement system* is incorrectly defined, does not have a clear purpose and is very different than the concept it replaced in 1996 (based on the containment system) [2]. Experience has shown, as expected, that the confinement system is often “forgotten” in the safety reports. The confinement system consists of packaging components and fissile material contents (excluding other components of the contents). In a recently reviewed package design involving a package consisting of a freight container with uranium pellets, the uranium was enriched to 1 % ^{235}U by mass. The confinement system was not mentioned in the safety report or in the authority approval certificate. The confinement system would be the ^{235}U contents (the fissile material contents) alone, since escape of the pellets from the packaging could not be excluded under accident conditions. ^{238}U is not fissile material and is by definition not present in the confinement system.

- No exemption limits for fissile material [2]. A microgram or less of any fissile nuclide in a radioactive material, package or consignment is enough to be a fissile material. Even if one of the exception types applies, there will still be fissile material in the radioactive material, package or consignment.

13. Natural uranium, a fissionable and fissile material supporting criticality in water

The formal status of natural uranium in the Regulations [1] is clear; the fissile nuclides in the natural uranium form a fissile material if the material is radioactive [2]. There is no fissile exemption limit. The exception types in para. 672 can be applied but they are more restrictive than necessary. E.g. the uranium must not form a lattice or be irradiated if the quantities are large. This excludes fresh fuel assemblies, rods and pellets. The fissile material definition in the Regulations [1] does not make sense and causes errors in the Regulations as well as in applications.

How should natural uranium be handled from a criticality safety point of view? If it is shipped separately from fissile nuclides in other materials and separately from large quantities of special moderators (deuterium, graphite and beryllium) there is no criticality hazard. If it is shipped together with other fissile nuclides, the criticality hazard can increase significantly. Natural uranium is a fissile material without presence of special moderators.

Two examples are mentioned here. The first involves addition of natural uranium slabs to a sub-critical and over-moderated solution with fissile nuclides. The system will go critical. The other example [18] involves adding a natural uranium slab between two identical transport packages with CSIs of zero. Again, the system will go critical.

The U.S. proposals in 2002 [15] for new exception types based on low concentrations of fissile nuclides are reasonable only if the fissile nuclides in natural uranium are included. This is probably not how the industry today applies the fissile material concept.

14. Conclusions

The criticality safety structure and quality of the Regulations has deteriorated since the first (1961) edition [11].

There has not been any criticality accident during transport yet, even though the JCO accident in 1999 involved preparation of fissile material for shipment.

The resources required for designing packages and shipping fissionable materials are often not justified by reduced hazards.

Human error has been the root cause of criticality accidents in the past and seems very likely in transport. Lack of structure and clear justification of requirements (transparency) together with clearly incorrect and inconsistent requirements increase the probability for and consequences of human error.

Often, the intent of a requirement is different than the text. The real intent may be difficult to find and this results in alternative interpretations by different people. This lack of quality reduces the weight of correct and justified requirements. Failure to comply with a requirement is justified by referring to a new interpretation of the real intent.

The Swedish proposals for revisions of the next edition of the Regulations are motivated by a desire to adapt the criticality safety structure and requirements to current as well as to future industrial needs while going back to the 1961 philosophy of safety, clarity, consistency and correctness.

15. References

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