WHY CONSIDERING CH2 MODERATION FOR EXCEPTED FISSILE MATERIAL?

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ABSTRACT

Paragraph 417(a) of the Regulations for the Safe Transport of Radioactive Material (2009 Edition) imposes mass limits for packages and consignments where the dispositions of the fissile material under Normal Conditions of Transport (NCT) or Accident Conditions of Transport (ACT) cannot be guaranteed. Therefore, it is proposed to revise these exceptions in paragraph 672 to strengthen these mass limits by requiring the use of the Criticality Safety Index (CSI).
To be consistent with the safety level required for certified packages, the calculated CSI must ensure that two groups of packages, each having a total CSI of 50, contain a subcritical mass. Under NCT, five groups of these packages must be safe.
Thus, proposed subparagraph 672(a) requires that a group of packages with a total CSI of 50 contains less than 1/5th of a given subcritical mass but the release of fissile material from the package is not limited. Proposed subparagraphs 672(b) and (c) require that a group of packages with a total CSI of 50 contains half a given subcritical mass and that the packages do not release their content under NCT. The values of the subcritical masses are provided in a table (Table M) for two cases depending on the moderator material: with restrictions (based on H2O moderation) and without restrictions (based on CH2 moderation).

This paper discusses the criticality issues related to the use of CSI calculated in case of restrictions. Indeed, since packages do not necessarily withstand the ACT or even NCT, ruined packages configurations cannot be excluded. Then, considering the fact that material used for transport may contain high density polyethylene (HDPE), retention trays, containers, bottles, pallets for example, or that packages could be transported alongside any other package carrying any hydrogenated material (CH2…), a fissile material from packages whose CSI has been calculated with restrictions can actually become moderated by a material whose hydrogen density exceeds the hydrogen density in water.
Different scenarios of consignments mixing packages approved using different cases of Table M have been studied. Results show that the mass of CH2 per consignment has to be lower than 500 g. Moreover if materials used for transport are taken into account, only the case without restrictions should be considered.

FISSILE EXCEPTIONS IN CURRENT REGULATIONS (PARAGRAPH 417)

Packages containing fissile material which meet the requirements in paragraph 417 of the Regulations for the Safe Transport of Radioactive Material (2009 Edition) [1] are excepted from requirements for packages containing fissile material. These exceptions were written so as to be

able to exclude a criticality accident except under incredible conditions. The criterion of interest in this paper, used in particular for waste shipments, is based on a limit of the fissile nuclides mass in the packages and in the consignment (417(a)i).

Paragraph 417(a)i imposes mass limits for packages and for consignments as a function of the moderator material. The maximum consignment mass, as shown in Table 1, is approximately half the critical mass value for U-235 and Pu-239. The mass of fissile nuclides per package, up to 15 g, is based on the work of Woodcock and Paxton [2], plus some practical considerations as explained in TS-G-1.1 [3]. This value allows to ensure distribution of fissile nuclides throughout the consignment to prevent the accumulation of fissile material thus reducing the potential criticality risk.
In addition, to take into account moderation and reflection by elements more efficient than hydrogen, restrictions are applied when beryllium and deuterium are present in the consignment.

Table 1. Consignment mass limits for exceptions from the requirements for packages containing fissile material in current regulations (2009 Edition)

Fissile nuclide	Fissile nuclide mass (g) mixed with substances having an average H density ≤ water	Fissile nuclide mass (g) mixed with substances having an average H density > water
U-235	400	290
Other fissile nuclide	250	180

Since the consignor has the best knowledge of the material shipped, he is in charge of the compliance with the provisions in paragraph 417. He has to ensure the material is properly packaged and prepared for transport. The carrier's role is limited to a few operational controls and to keep personnel away from packages to limit radiation exposure. This does not prevent coincident multiple consignments, individually categorized as fissile material exceptions, from being transported on a single conveyance. Thus, subcritical mass limits of fissile material could be exceeded. This shows that shipment controls have to be extended to cover more than the single control of the fissile mass per consignment.

Therefore, it is proposed to revise this exception to strengthen these mass limits by requiring the use of a Criticality Safety Index (CSI). This proposition is the outcome of discussions in an international working group from IAEA's Transport Safety Standards Committee (TRANSSC) for reviewing the fissile exceptions and making recommendations for improvement (see [6]).

PROPOSITION OF REGULATION MODIFICATION (PARAGRAPH 672) [4]

To be consistent with the safety level required for certified packages, the use of CSI must ensure that two groups of damaged packages, each having a total CSI of 50, contain a subcritical mass. Under normal conditions of transport (NCT), five groups of these packages must be safe.

Then, to introduce CSI for exceptions from the requirements for packages containing fissile material, two types of situations are considered according to the need or not of mechanical and thermal qualifications in normal conditions of transport. In order to ensure that fissile material is more or less distributed throughout the consignment when it is constituted by several packages, the

value of CSI for each package should not exceed 10. So, if the consignment is maximal (CSI = 50) then the fissile material is divided out in at least 5 packages (the consignment shall be transported under exclusive use if its CSI is greater than 50).

In addition, in order to adapt the regulations to current and future needs and to make them more flexible, mass limits of uranium are proposed as a function of U-235 enrichment present in the nuclear facilities. Indeed, most of the nuclear facilities handle uranium with low U-235 enrichments. In this case, the 15 g limitation of the mass of fissile nuclides in packages is not a real benefit in terms of criticality safety but it increases the other risks (more transports lead to increased radiation doses). Transports of radioactive wastes are concerned in particular. Given that many nuclear facilities are nearing decommissioning, the transport of wastes is going to increase significantly in the next years.

The values of the maximal mass of fissile material in a package complying with the requirements of paragraph 672 (with a CSI of 10) are provided in Table 2 when there is no mixture of fissile materials with different uranium enrichments. For low U-235 enrichment, the maximal masses of U-235 per package are clearly higher than the present value of 15 g, which allow an optimisation of the volume of packages without increasing significantly the criticality risk.

- The column entitled “limited use” concerns packages for which it can be ensured that there is no more than 20 g of material with a hydrogen density greater than water and the column entitled “general use” concerns the other cases.
- The columns entitled “No test” concern packages for which the tests defined in the regulations for simulating NCT are not required (paragraph 672(a)) and the columns entitled “NCT test” concern packages that can withstand these tests and whose smallest external dimension is greater or equal to 30 cm (paragraph 672(b)).

Table 2. Maximal fissile nuclide mass per package that can be transported applying paragraph 672 in the current revision of regulations

Fissile nuclide	Uranium enrichment in mass percent of U-235 not exceeding	Maximal mass per package (g) – CSI = 10			
		General use		Limited use	
		No test	NCT test	No test	NCT test
U-235	1.5	80	200	96	240
	5	30.8	77	40	100
	10	22	55	32.4	81
	20	18.8	47	28	70
	100	14.4	36	21.6	54
Other fissile nuclides	Not Applicable	9.2	23	14	35

To make transition with current regulations, it is also possible, with paragraph 672(c), to transport 15 g of fissile nuclides in packages provided that their smallest external dimension is equal to 10 cm after normal conditions of transport tests and that the consignment mass limit is the same as the one from paragraph 672(b).

Moreover the headers of Table 1 "… mixed with substances having an average hydrogen density…" are modified in the table proposed in the current revision of the regulations for two reasons:

- only the hydrogenous substances *mixed* with fissile material could be considered in this case (other hydrogenous substances of the packages are not always taken into account),
- when all the hydrogenous substances in the packages are considered, the average hydrogen density can be lower than water, even if there is high density polyethylene (HDPE).

Finally, it has to be pointed out that the proposed modification of the regulations is not validated yet. One of the points to be discussed by TRANSSC members concerns the fact that the demonstration of resistance of the packages to the tests specified in the regulations for normal conditions of transport is validated only by the consignor who is also responsible for the preparation of the packages. This is a weak point for paragraphs 672(b) or (c) if the target is to ensure an equivalent safety level to the one for certified packages. Another point to be discussed is the presence of moderator materials with a hydrogen density greater than water in the consignment and the way they are taken into account. The present paper is essentially about this last point.

CALCULATION OF CSI IN CASE OF RESTRICTIONS

Packages containing materials with an average hydrogen density less than water are in the scope of the "limited use" case for the calculation of CSI. When materials with a hydrogen density greater than water are present in packages, lower mass limits must be considered. In the other cases, the CSI of the packages will be calculated applying values in the "limited use" column because mass limits of fissile nuclides are higher. This may represent an issue if under some transport conditions, materials with a hydrogen density greater than water can be mixed with material in packages whose CSI has been calculated with restrictions.

Scenarios

A consignment with a CSI equal to 50 can be constituted by a mixture of packages with CSIs coming from calculations for "general use" case and for "limited use" case. However since packages do not necessarily survive the accident conditions of transport (drop tests, fire test and water immersion test) or even normal conditions of transport, scenarios of ruined packages cannot be excluded. Then, if some of the packages of the consignment do not contain for example HDPE, the HDPE coming from the other packages could be mixed with the fissile material of the first packages in a scenario of ruined packages and subcritical mass for a group of packages could be exceeded. This is a new issue in comparison to the current regulations which define a single mass limit criterion for the whole consignment.

Some examples of consignments mixing packages with CSI coming from calculation for "general use" case and for "limited use" case are given below.

Example 1

If there is no demonstration that packages withstand the tests defined in the regulations for normal conditions of transport, a consignment may be composed of 5 packages with 20 g of U (100% U-235 enrichment) without polyethylene ($CSI_{package}$=9.26) and of 1 package with 1966 g of U (1.5% U-235 enrichment) where polyethylene is authorised ($CSI_{package}$=3.69). To be consistent with the

objective of the regulations, five consignments (ruined packages) should be subcritical i.e. 500 g of U (100% U-235 enrichment) and 9830 g of U (1.5% U-235 enrichment) with polyethylene (figure 1).

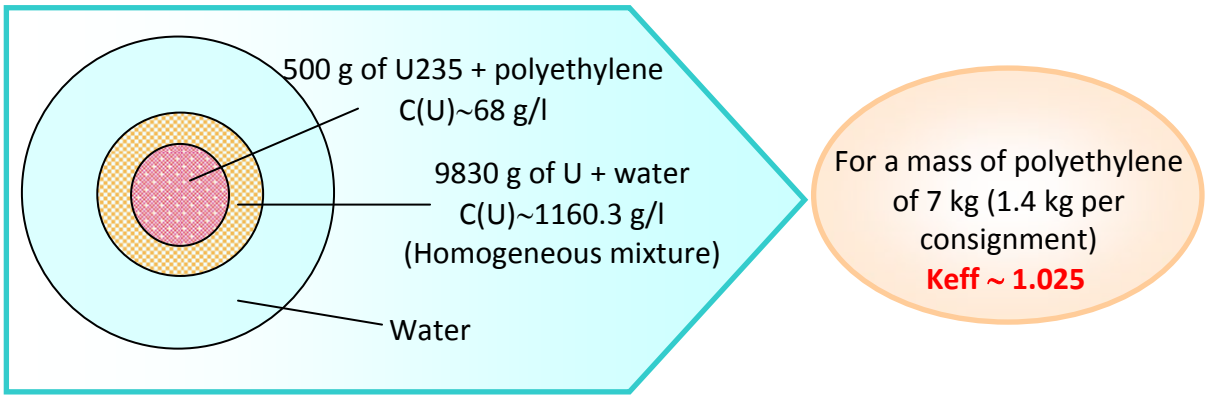

Figure 1. Configuration for example 1

For packages withstanding the tests defined in the regulations for normal conditions of transport, the same conclusions can be obtained for a consignment composed of 5 packages with 50 g of U (100% U-235 enrichment) without polyethylene ($CSI_{package}$=9.26) and of 1 package with 4915 g of U (1.5% U-235 enrichment) where polyethylene is authorised ($CSI_{package}$=3.69) and for which, according to the objective of the regulations, two consignments need to be considered.

Example 2

If packages resist to the tests defined in the regulations for normal conditions of transport, a consignment can be composed of 5 packages containing 1.6 kg of U (5% U-235 enrichment) without polyethylene ($CSI_{package}$=8) and of 1 package containing 13.33 kg of U (1.5% U-235 enrichment) where polyethylene is authorised ($CSI_{package}$=10). The configuration to consider comprises two consignments i.e. 16 kg of U (5% U-235 enrichment) and 26.67 kg of U (1.5% U-235 enrichment) with polyethylene (figure 2).

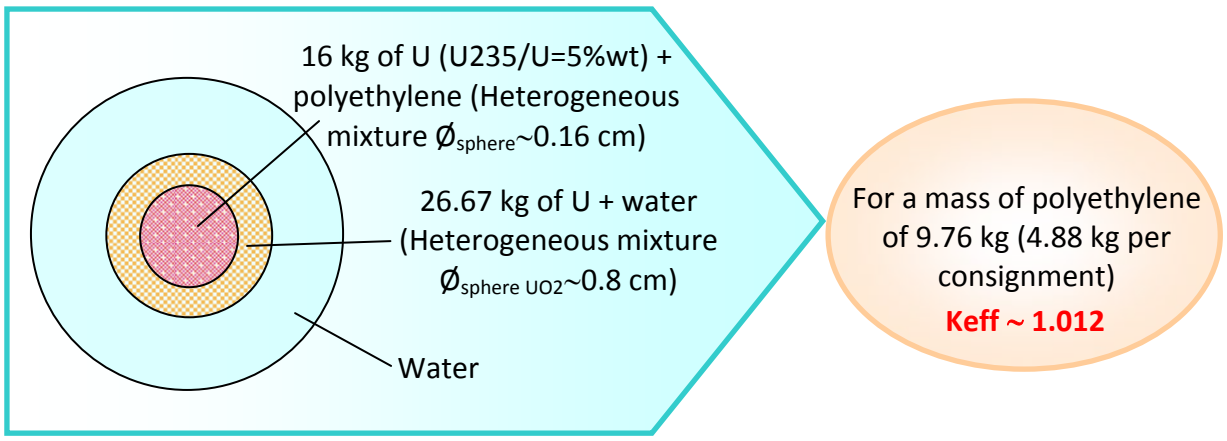

Figure 2. Configuration for example 2

The above examples show that unacceptable keff values can be obtained in the case of consignments mixing packages with CSI coming from calculation for “general use” case and for “limited use” case. Moreover, further calculations show that the mass of polyethylene per consignment has to be lower than 500 g to be subcritical.

In addition, many materials used for transport contain HDPE (retention trays, containers, bottles, pallets, etc.). For certified packages, because of the demonstration that packages withstand tests defined in the regulations for normal and accident conditions of transport, the materials used for transport are not often taken into account. Nevertheless hydrogenous moderation between damaged packages has to be considered. These materials should be considered when there is no demonstration that packagings do not release their contents, which is the case of fissile packages complying with the requirements of paragraph 672. This problem already exists in current regulations for fissile excepted packages. As the mass limit of fissile nuclides of the consignment only takes into account the presence of hydrogenous substances mixed with fissile nuclides and not polyethylene present in the consignment, criticality risk cannot be excluded in accident scenarios. However, as a maximum of 15 g of fissile nuclides is a priori loaded in each package, it is necessary to damage, in most cases, more packages than in the proposed draft of the regulations to reach a critical configuration.

What the regulations say

These above scenarios take into account a rearrangement of the content of packages arrays, in accordance with the potential worse case of the effects of tests specified in the regulations.

Indeed, this scenario is derived from the requirement defined in paragraph 682(c) of the regulations applicable to packages containing fissile materials (concerning assessment of package arrays under accident conditions of transport), the fissile material that escapes from each package shall be arranged in the configuration and moderation that results in the maximum neutron multiplication with close reflection by at least 20 cm of water.
It is expected, for certified packages, the release of only a little quantity of fissile material from the containment system of each package of an array under accident conditions of transport but all the precautions to prevent it should be taken. So, paragraph 682(c) provides a severe restriction to consider the possible configurations for fissile material escaping from the containment system and the chemical or physical changes. Moreover, the scenario consisting in gathering fissile materials in packages complying with the requirements of paragraph 672 is not less credible than the one for packages containing fissile materials for which paragraph 682(c) is applicable. Then, the considerations of paragraph 682(c) should be taken for packages according to paragraph 672(b) or (c) that can be ruined under accident conditions of transport. Moreover, since fissile materials can escape from the containment system for packages according to paragraph 672(a) even in normal conditions of transport, these considerations should be extrapolated to arrays of packages under normal conditions of transport.

In addition, it has to be pointed out that a hydrogenous moderation has to be considered between the damaged packages of an array according to paragraph 682(a) of the regulations. For certified packages, the maximum neutron multiplication of an array of a sufficient number of packages is generally obtained for interstitial moderations lower than water. In fact, as fissile material generally remains in the confinement system of the packages, moderation between packages often reduces

their interactions. Since the confinement of the fissile material is not required in paragraph 672, the maximum neutron multiplication may not be obtained for moderation between packages lower than water.

Then, transposing these two paragraphs to the proposed paragraph 672, where loss of the containment system of each package must be assumed, the worst assumptions regarding the geometric arrangement of fissile material and moderation conditions should be made, taking into account all moderating components, at least, of the consignment. Obviously, the assumptions have to be very severe if the packaging could disappear after a fire for example (figure 3).

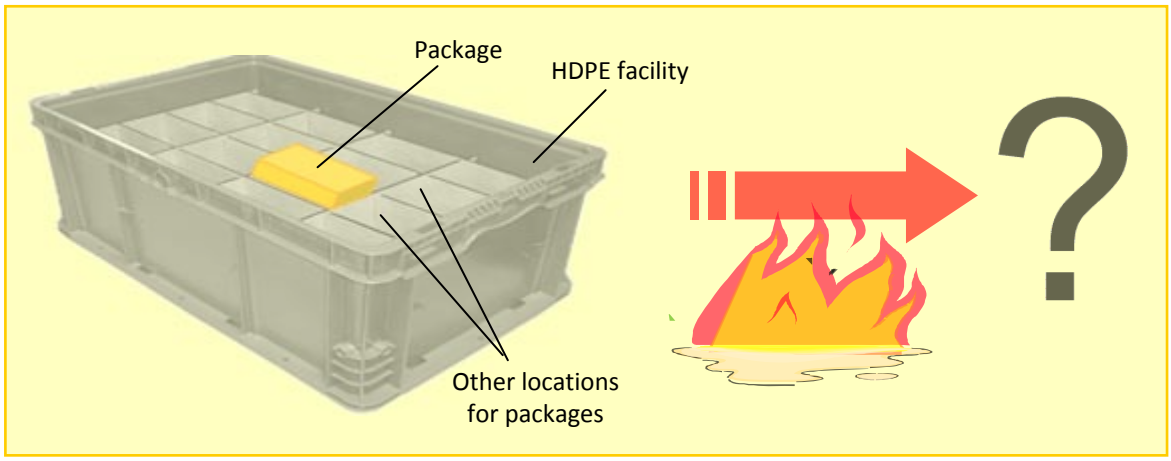

Figure 3: Accident scenario of a consignment of packages applying paragraph 672

Margins evaluation

In the proposed paragraph 672, the consignor is responsible of the characteristics of transported materials, the preparation of packages and, in some cases, the verification of the minimal external dimension of packages taking into account the results of regulations tests made appropriately.
Then the consignor will validate that, with the margins he took, the fissile material in each package is not under-estimated. He will also decide which column of table M applies for each package.

In the current regulations, even if fissile material is not always easy to estimate, in particular in wastes, some errors concerning the mass of each package could be acceptable because of :

- the dissemination of the fissile material throughout the consignment in packages of 15 g,
- the uranium enrichment in U-235 is not taken into account,
- the consignment mass limit considered when it is constituted by at least one package with substances having hydrogenous densities greater than water is the lowest one.

In the proposed paragraph, the limit of fissile mass per package can be higher because uranium enrichment is considered. Moreover fissile material can be less distributed throughout the consignment because the consignment mass limit can be reached with only five packages. Nevertheless, if the underestimation of the fissile mass of each package remains low, the error could be acceptable. But, the possibility to mix packages with substances having hydrogenous densities greater than water and packages with substances having hydrogenous densities equal to or lower than water without restraining the consignment mass limit to the lowest one is completely different from current regulations and lead to increase criticality risk significantly.

As for the verification of the behaviour of packages to the regulations tests needed in paragraphs 672(b) and 672(c), it is not a competence of the consignors. Then, both paragraphs should be improved to achieve the safety level expected.

Finally, if all the margins existing in current regulations are cut down, the assumption concerning the reflection of 20 cm of water considered until now should be discussed. For example, reflection of fissile material by 30 cm of steel could lead to reduce the subcritical mass to around 75 % of the current values.

CONCLUSIONS

Considering proposed paragraph 672, it is not desirable to mix packages whose CSI is obtained from “general use” case and from “limited use” case or to mix packages from “limited use” with non-radioactive packages or transport facilities or materials containing substances having a hydrogen density greater than water. When the CSI of packages is calculated for a “limited use” case, at least a limit of mass of polyethylene per consignment is necessary. The calculations performed are not exhaustive and do not cover all the cases but they show that the mass of polyethylene per consignment has to be lower than 500 g. The limit of 20 g for substances with a hydrogen density greater than water in a package applying to the case of “limited use” as proposed in the draft of the regulations is not sufficient.

Besides, since many transport facilities are made of HDPE, it could be not easy to comply with this consignment limit. To guarantee subcriticality of consignments, it is therefore recommended to restrict the use of Table M to the values of the column “general use”. If necessary, redefining the mass values in this column may be envisaged to lighten the impact of this recommendation.

In any case, occurrences of HDPE equipments are increasing in transport and the current regulations are also concerned. A solution should be sought.

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