MIXING OF PACKAGE DESIGNS: NUCLEAR CRITICALITY SAFETY*

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Abstract

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International transport regulations incorporate rules for mixing package designs during transport, including transit storage. Permissible combinations of packages are based on transport indexes. In the paper, two main types of flaws in the rules for mixing package designs have been defined and investigated. (1) Reduced leakage of neutrons from a group of packages. A package which has a high reactivity value in the centre of an array may have a low value on the outside. For another type of package, the opposite may be true. A special case is a non-fissile package. (2) Increased neutron coupling between packages. Sometimes safety depends on the extent of neutron absorption in the packaging materials. Similar packages can be almost entirely isolated from each other. Mixing of such packages with others can reduce the neutron-absorbing effect of the packagings. Flaws are the result of physical relations that can be understood without the need for complicated calculations. However, calculations of a few examples have been made. The findings of the study are that the rules for the mixing of package designs are questionable. General application of the rules may lead to a considerable deterioration in safety. Another conclusion is that a thick layer of concrete, lead or iron on one side of a cube-shaped configuration of packages may provide a lower level of safety than water on all six sides. In the long term, a change in the transport regulations is recommended in order to give due consideration to those cases in which a mixing of package designs would not provide an adequate level of safety.

1. INTRODUCTION

International transport regulations for the transport of fissile materials (based on the Recommendations of the IAEA [1]) permit mixing of package designs. Permissible combinations of packages are based on transport indexes. These indexes are determined for each individual package design. Similar rules are also applied on a national level in connection with the storage and handling of fissile materials.

In 1981, the IAEA took up the question of possible flaws in the rules for mixing of package designs. It was recommended that the studies continue even if no clear indications of such flaws were found [2]. Following a request from the IAEA, the question was dealt with by a working group under the direction of the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA). Some calculations were made, but a restricted time schedule meant that the matter was left open for further consideration [3].

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2. RULES FOR MIXING OF PACKAGE DESIGNS

For each package design intended for fissile materials, an 'allowable number' must be determined. This includes analyses of different combinations of mechanical, fire and water immersion tests. To a certain extent, administrative shortcomings that lead to the number of packages increasing above the allowable number must be considered. In addition, each configuration of packages shall be 'reflected' on all sides by water. The transport index for each package design is 50 divided by the allowable number (radiation outside the package sometimes leads to the transport index being raised). The rules for mixing of package designs are the same as if all packages were of the same design. The accumulated transport index for all packages must not exceed 50 or, in the case of a full load, 100.

3. MAIN TYPES OF FLAWS IN THE RULES FOR MIXING

At the beginning of the study, two main types of flaws in the rules for mixing were identified. In this section, the flaws are explained, while examples and calculations follow in Sections 5 and 6.

3.1. Reduced neutron leakage

For package designs with a limited allowable number, the leakage of neutrons from a configuration of fissile packages is of importance with regard to safety. This leakage is influenced by various materials outside the configuration of fissile packages in that there is a certain degree of neutron reflection. If there are different types of fissile packages, the leakage is affected by how the packages are positioned in the configuration. In order to demonstrate the importance of leakage and reflection, three configurations are shown (Fig. 1). Each square symbolizes the cross-section of a long package.

Figure 1(a) shows a 5×5 array of package design 1. In an infinite number this package design would give high neutron multiplication. In a limited number, safety requirements are met through considerable leakage of neutrons, even if some are reflected by the water surrounding the array. The water-reflected 5×5 array is safe. Figure 1(b) shows a mixed 5×5 array of package designs 1 and 2. To what extent the safety is affected by mixing depends on the quantity (and to a certain extent the energy spectrum) of neutrons returned to the central part of the array by the outer layer of packages, together with the water reflector. It is obvious that mixing of this type can reduce the degree of safety. In Fig. 1(c), package design 3 has been introduced into the configuration shown in Fig. 1(a). The transport index for package design 3 is 0. Consequently, the number of these packages that can be mixed with packages of design 1 is unlimited. In this case it is even more obvious that the mixing can reduce the degree of safety.

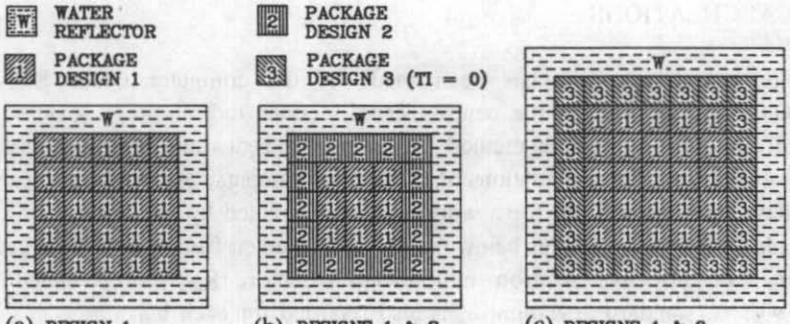

FIG. 1. Reduced leakage possibilities.

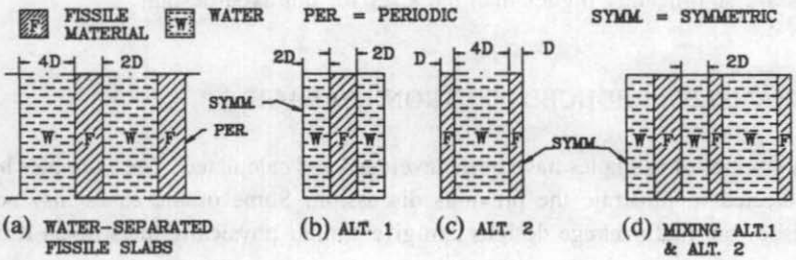

FIG. 2. Demonstration of increased neutron coupling.

3.2. Increased neutron coupling between packages

The neutron absorption effect of a packaging wall depends on the material type and thickness. For packages of the same design, the fissile materials in different packages are separated by two wall thicknesses.

Figure 2(a) shows a simplified model of an infinite number of slabs (assumed to be infinite in two dimensions). The only two materials are fissile material and water. The water slab is so 'thick' that the neutron coupling between the fissile slabs is very limited. Owing to this, the neutron multiplication will be safe for an infinite number of slabs, arranged as in Fig. 4. This model can be used to design a fissile package with water representing a packaging material. Two alternatives can be constructed (see Figs 2(b) and 2(c)). In Fig. 2(b), the packaging walls go through the middle of the water slabs shown in Fig. 2(a), whereas in Fig. 2(c) they go through the middle of the fissile slabs. Figure 2(d) shows how a mixture of the two alternatives can result. The water separation is halved between some of the fissile contents of a mixed configuration of package designs. It is again clear that the mixing can lead to reduced safety.

4. CALCULATIONS

For calculations use has been made of the computer codes KENO-V and NITAWL, as well as the neutron cross-sections in 27 energy groups from SCALE [4]. The calculation method, including the codes and cross-sections, has been validated through calculations of critical experiments. Some of those calculations have been carried out for a working group directed by the NEA [3, 5]. The materials used in the examples below have also been taken from the working group's studies. The effective neutron multiplication factor, k_{eff}, is calculated with KENO-V. A standard deviation, σ, is also reported for each k_{eff}.

It should be noted that the calculation models were chosen to demonstrate the flaws in the mixing rules. The calculated k_{eff}'s are, in many cases, too high to be acceptable in any real application. However, the k_{eff}'s for the mixed-package designs are significantly higher than the k_{eff}'s for unmixed designs.

5. EXAMPLES: REDUCED NEUTRON LEAKAGE

A number of examples have been developed and calculated. The examples have been selected to illustrate the previous discussion. Some of the cases may seem unrealistic, but real package designs can give similar physical effects (even if they are not so extensive).

5.1. Large number of ^{235}U metal and non-fissile packages

A model from the NEA's working group is taken as a reference case [3]. The package design consists of a cube-shaped package containing a sphere with metallic ^{235}U. There is no packaging material. In order to secure a safe margin to criticality, the radius of the sphere is slightly decreased, i.e. from 6.242 to 6.1 cm.

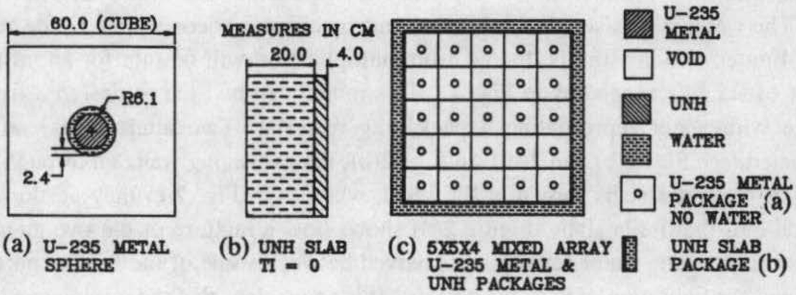

FIG. 3. Reduced leakage (no packaging material except water).

TABLE I. FISSILE PACKAGES SURROUNDED BY NON-FISSILE PACKAGES

CASE NO.	NO. OF PACKAGES	ARRAY SHAPE	WATER SHELL T (CM)	OUTSIDE PACKAGE MATERIAL	THICK-NESS (CM)	K_{EFF}	σ
1	1	1x1x1	20.0	NONE	0	0.966	0.0080
2	512	8x8x8	0.0	WATER	20	0.962	0.0085
3	216	6x6x6	0.0	WATER	20	0.902	0.0066
4	216	6x6x6	2.4	WATER	20	0.935	0.0075
5	216	6x6x6	0.0	LEAD	40	1.070	0.0070
6	100	5x5x4	0.0	LEAD	40	0.991	0.0068
7	100	5x5x4	2.4	LEAD	40	1.070	0.0077
8	27	3x3x3	2.4	LEAD	40	0.985	0.0084
9	8	2x2x2	2.4	LEAD	40	0.937	0.0071
10	216	6x6x6	2.4	LEAD	20	1.054	0.0082

If the allowable number is to be 100 (transport index 0.5), 500 undamaged packages and 200 'damaged' packages will be subcritical in a cubic configuration reflected by water. A damaged package is assumed to have an unchanged geometry, but with a 2.4 cm thick water layer (shell) outside the sphere (Fig. 3(a)). Since packages containing concrete, lead, steel or natural uranium are not given a transport index, they can be placed outside the configuration during transit storage or transport. The calculation model is similar to Fig. 1(c) without the water reflector.

Table I shows the results of a number of calculations. The first four calculations refer to cases that are required according to the regulations. These are followed by six cases which show the effect of lead packages outside the central configuration of fissile packages. The results show that safety may be reduced substantially if fissile and non-fissile packages are mixed.

5.2. ^{235}U metal and UNH packages (transport index 0)

The ^{235}U metal package design is the same as in the previous example (Fig. 3(a) without water). The uranium nitrate solution (UNH) packages consist of large, flat packages of UNH and water, with the uranium consisting of 100% ^{235}U. The material data for UNH are also taken from Ref. [3].

In order for a package design, as shown in Fig. 3(b), to meet the requirements of the regulations for a transport index of 0, an infinite number of packages must be safe. The limiting case is obtained if the UNH layers are turned towards each other. According to the NEA's studies, water between the UNH layers does not lead to any significant increase in k_{eff}. For an infinite number of packages, k_{eff} is 0.934 (σ = 0.0086).

Figure 3(c) shows the calculation model for ^{235}U metal packages without water layers surrounded by UNH packages. For this mixed array k_{eff} is 1.056

TABLE II. FISSILE AND NON-FISSILE PACKAGES (NEUTRON-ABSORBING WALLS)

CASE NO.	NO. OF PACKAGES	ARRAY SHAPE	OUTSIDE PACKAGE MATERIAL	THICKNESS T (CM)	K_{EFF}	σ
11	512	8x8x8	WATER	20	0.967	0.0072
12	100	5x5x4	LEAD	40	1.106	0.0078
13	100	5x5x4	STEEL	40	1.036	0.0071

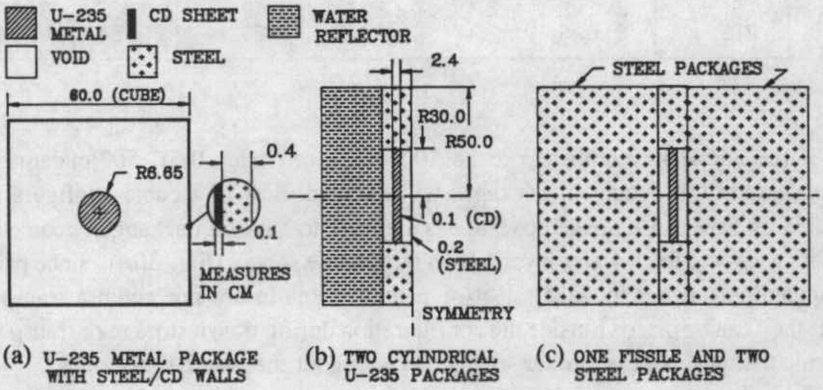

FIG. 4. Reduced leakage (fissile packages including packaging materials).

(σ = 0.0084). In other words, the addition of packages with a transport index of 0 may give a lower level of safety.

5.3. ^{235}U metal/cadmium and non-fissile packages

Consideration of the packaging materials does not change the conclusions from earlier examples, but rather reinforces them. On the basis of earlier ^{235}U metal packages, wall materials of steel and cadmium (Cd) (as in Fig. 4(a)) are added. The package design does not allow in-leakage of water during testing. The radius of the sphere can be increased to 6.65 cm.

Three different cases are calculated. The first refers to 512 (8×8×8) ^{235}U metal packages with water reflection. This meets the requirements with regard to undamaged packages and an allowable number of 100. The other two cases concern 100 ^{235}U metal packages surrounded by a 40 cm thick layer of lead or steel packages, respectively. The results are shown in Table II.

Comparison with the example in Section 5.1 shows that the packaging material can reinforce the effects of mixing. This is only to be expected since water produces moderation, which increases the absorption in the packaging material. Such moderation is not obtained from materials with low contents of hydrogen.

5.4. Mixing a cylindrical ^{235}U/Cd package with two steel packages

Figure 4(b) shows a model of two 'damaged' cylindrical packages with water reflectors on two sides (symmetry used). The ^{235}U, Cd and steel materials are the same as previously. Since the k_{eff} is calculated to be 0.940 (σ = 0.0075), this can be regarded as a package design with a transport index of 50. In the example shown in Fig. 4(c), a single fissile package is mixed with two 40 cm thick steel packages, one on each side. Here, the k_{eff} is calculated to be 1.005 (σ = 0.0061).

6. EXAMPLE: INCREASED NEUTRON COUPLING BETWEEN PACKAGES

6.1. Package designs with UNH or ^{235}U metal in slab shape

Figures 2(b) and 2(c) give examples of two different package designs which, in infinite numbers, are similar to the example in Fig. 2(a). The fissile material is UNH, its total width in both package designs being 7.0 cm. The total water width is 14.0 cm.

A modified package design is also introduced for ^{235}U metal instead of UNH. Since water between two ^{235}U metal slabs would increase the k_{eff}, only the example in Fig. 2(b) was used as a basis for a ^{235}U metal package design. The ^{235}U width is 0.4 cm, while the total water width is still 14.0 cm. The results are shown in Table III. It can be seen that despite the fact that all three package designs have a transport index of 0, criticality cannot be excluded.

TABLE III. MIXING TWO PACKAGES WITH TRANSPORT INDEXES OF 0

CASE NO.	PACKAGE DESIGN 1		PACKAGE DESIGN 2		K_{EFF}	σ
	MATERIAL	FIGURE	MATERIAL	FIGURE		
17	UNH	2(B)	UNH	2(B)	0.959	0.0073
18	UNH	2(B)	UNH	2(C)	1.040	0.0067
19	U-235	2(B)	U-235	2(B)	0.944	0.0072
20	U-235	2(B)	UNH	2(B)	0.957	0.0073
21	U-235	2(B)	UNH	2(C)	1.056	0.0071

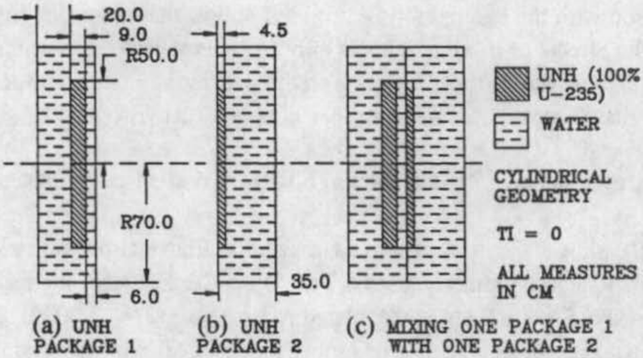

FIG. 5. Increased coupling (total transport index: 0).

6.2. Two packages of different designs with transport indexes of 0

Consider two package designs which, in damaged condition, are similar to the examples in Figs 5(a) and 5(b). The materials are water and UNH, as in earlier examples. For an infinite number of packages, in accordance with Fig. 5(a), and with the thin layers of water facing each other, k_{eff} is calculated to be 0.974 (σ = 0.0075). This is somewhat high, but is used here only for the sake of comparison. The fissile materials in different packages are separated by at least 12.0 cm of water. An infinite number of packages, according to Fig. 5(b) gives a lower k_{eff}. If two packages, one of each design, are placed together, according to Fig. 5(c), the separation between the fissile materials is only 6.0 cm of water. For this case, with only two packages with transport indexes of 0, k_{eff} is 1.043 (σ = 0.0084). This is clearly higher than for an infinite number of the one-package design.

7. CONCLUSIONS AND RECOMMENDATIONS

The studies have shown that mixing package designs during transport can result in a lower level of safety. It cannot be excluded that criticality occurs even if all rules are adhered to and the packages are not damaged. For example, reflection by concrete, lead or iron on one side of a configuration of packages can result in a lower level of safety than water on all sides of the configuration. A package design often includes various options for both contents and packagings. The results for the mixing of package designs can be extended to the mixing of different options or different 'damages' of the same package design.

In the long term, it is recommended that the rules for mixing package designs should be changed. In addition, it is recommended that the rules for neutron reflection should be changed so that the realistic effects of concrete and other materials can be accounted for.

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