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Status of revision

English version	French version	Date	Purpose and record of changes	Prepared by / Checked by
Old reference : DOS-13-00081778-500				
00	00	04/2012	First issue – Revision of Appendix 11 of Safety Analysis Report TFXDC 2158 revision H and Appendix 12 of Safety Analysis Report TFXDC 2159 revision G.	
01	01	09/2012	Appendix 2.5-4 added – Justification of the increase in cavity cross section, from [redacted] x [redacted] mm² to [redacted] x [redacted] mm².	
02	02	12/2015	Inclusion of the potential presence of a maximum of 5 g of glycerine on the fuel assemblies.	
03	03	12/2016	Deletion of reference <2>, – FF DC 00561 rev C: Transport packages for fresh UO2 fuels. Determination of uncertainties to be applied in criticality studies performed with CRISTAL. Appendix 2.2-5 added – Inclusion of contents XL and EPR used to increase the cavity cross section to [redacted] x [redacted] mm². Appendix 2.2-6 added – Determination of uncertainties to be applied to criticality studies performed with CRISTAL. Shift of the paragraph in Chapter 2.1-13, dealing with the impact on -criticality safety of the smooth-walled dummy to this chapter. Addition of the impact of damage on the door for the internal fittings in FCC3 and FCC4 packagings, after a 1m drop onto a bar at the maximum temperature reached during NCT. Integration of 17x17 GAIA 14-foot assemblies	
1.0	04	10/2020	– Addition of a potential thickness of chrome, excess thickness or not, onto the rods cladding zirconium alloy	
New reference: DOS-19-021165-014-NPV				
1.0	1.0	See first page	– Deletion of the case of limited number of rods without wedging. – Addition of reference <3>, which justify that the model of [redacted] package arrays used in demonstration of Appendices 2.5-1 and 2.5-5 is penalizing compared to [redacted] package arrays. – Formal modifications.	

BRAND NAMES

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Summary

The purpose of this Chapter is to describe the criticality-safety analysis of the FCC3 and FCC4 model packages in conditions of transport according to the regulations (reference <1>) applicable to industrial type containers loaded with fissile materials.

This analysis includes:

- The criticality-safety analysis of the FCC3 and FCC4 packagings loaded with assembly types 15x15, 17x17 12-foot, 17x17XL, XLR and GAIA, 17x17 EPR type, 16x16 and 18x18,

- The criticality-safety analysis of the FCC3 packaging version 2, loaded with assembly types 14x14 - 8-foot and 14x14 - 10-foot.

- The criticality-safety analysis of the FCC3 and FCC4 packagings loaded with rods in boxes.

The analyses were conducted on the package in isolation and on an array of packages with the same criterion in both configurations: $K_{eff} \leq 0.95$, all uncertainties included.

Criticality-safety is ensured for the FCC3 and FCC4 packagings loaded with assembly types 15x15, 17x17 12-foot, 17x17 XL, XLR and GAIA, 17x17 EPR, with a CSI = 0.625.

Criticality-safety is ensured for the FCC3 and FCC4 packagings loaded with assembly types 16x16 and 18x18, with a CSI = 8.33.

Criticality-safety is ensured for the FCC3 and FCC4 packagings loaded with type 14x14 assemblies, with a CSI = 0.

Criticality-safety is ensured for the FCC3 and FCC4 packagings loaded with non-assembled fuel rods in boxes, with a CSI = 0.

Finally, gadolinium-bearing rods with a minimum content of 2 % on a matrix with a maximum uranium-235 enrichment of [redacted] % can be transported irrespective of the number of rods and type of packaging used. These rods have a $K_{infinite}$ value less than 1.0 irrespective of the moderation used.

Respect for the criticality-safety criteria of the FCC4 Version 1 and FCC3 Version 1 packagings, loaded with non-assembled rods or fuel assembles, is not brought into question for cavity cross sections of up to [redacted] mm x [redacted] mm.

The presence of glycerine (max. 5g) does not make any difference to the conclusions of the criticality-safety analyses.

The presence of a smooth-walled dummy or EPR assembly model does not make any difference to the conclusions of the criticality-safety analyses.

The presence of chrome localized on the rods cladding (in excess thickness or not onto the zirconium alloy) does not make any difference to the conclusion of the criticality-safety analysis.

1. Purpose

The purpose of this Chapter is to describe the criticality-safety analysis of the FCC3 and FCC4 model packages in conditions of transport according to the regulations (reference <1>) applicable to industrial type containers loaded with fissile materials.

This analysis includes:

- The criticality-safety analysis of the FCC3 and FCC4 packagings loaded with assembly types 15x15, 17x17 12-foot, 17x17XL, XLR and GAIA, 17x17 EPR type, 16x16 and 18x18,
- The criticality-safety analysis of the FCC3 packaging version 2, loaded with assembly types 14x14 - 8-foot and 14x14 - 10-foot.
- The criticality-safety analysis of the FCC3 and FCC4 packagings loaded with rods in boxes.

The analyses were conducted on the package in isolation and on an array of packages with the same criterion in both configurations: $K_{eff} \leq 0.95$, all uncertainties included.

2. Input data

2.1. Note on regulatory context

These containers are categorised as "Type II Fissile Industrial Packages" in accordance with IAEA Regulations (reference <1>) and must by design ensure sub-criticality for a container in isolation or a number of containers in Routine Conditions of Transport (RCT), in Normal Conditions of Transport (NCT) and in Accidental Conditions of Transport (ACT), all in accordance with IAEA Regulations (reference <1>).

Compliance with Criticality-safety is ensured for conditions of maximum neutron multiplication.

The analyses were conducted on the package in isolation and on an array of packages with the same criterion in both configurations: $K_{eff} \leq 0,95$, all uncertainties included (See Appendix 2.5-6).

2.2. Description of packagings and contents

A description of the packagings is given in Chapter 1.4 of the FCC3 and FCC4 Safety Analysis Reports.

A description of the contents is given in Chapter 1.3 of the FCC3 and FCC4 Safety Analysis Reports.

The FCC packaging model involves confining the fuel inside a volume of known cross-section that is as small as possible and mechanically guaranteeing that this geometry is preserved on completion of regulatory tests.

The isolation system is described in Chapter 1.4 of the Safety Analysis Reports for the FCC3 and FCC4 packagings.

The packages have no specific characteristics designed to prevent the infiltration of water; the presence of a given quantity of water is therefore assumed within the empty spaces of the package.

The damaged condition of the package is then defined as that resulting from the cumulative effect of the tests representative of normal conditions of transport and accidental conditions of transport (See Chapters 2.1 and 2.2 of the FCC3 and FCC4 Safety Analysis Reports). This package condition covers the regulatory conditions defined by paragraphs 682 b) and c) for the package in isolation, and by paragraphs 684 and 685 for multiple packages.

The undamaged condition of the package is then defined as that resulting either from routine conditions of transport or from drop tests in normal conditions of transport with regard to the slight damage possible to the shells of the packaging (slight localised indentation; see Chapter 2.4).

The fuel rods remain intact and the cross-section of the packaging remains unchanged at the end of the regulatory tests. Details of the calculation cases considered are given below.

3. Calculation method

Appendix 2.5-6defines the uncertainties to be applied when using the CRISTAL form for the transportation of fresh UO2 fuels.

The number (N) of packages, as defined by Articles 684 and 685 of reference <1>, which can be transported from a criticality-safety standpoint is used to determine the Criticality-Safety Index (CSI) by the formula:

CSI = 50 / (min (N^{NCT} ; N^{ACT}))

3.1. Isolated package

The package in isolation, damaged or in routine condition (undamaged), must be sub-critical with a total reflection by a 20 cm layer of water around the enclosure.

3.1.1. Package in isolation undamaged

The configuration studied is: package undamaged (cylindrical model) filled with water and surrounded by a reflector of 20 cm of water.

3.1.2. Isolated, damaged package

The geometrical configuration studied is: package damaged (rectangular model) surrounded by a reflector of 20 cm of water.

The space between the cavity and the shell is:

- either full of water (the package is also filled with water),
- or filled with vacuum (differential draining of the package is considered).

3.2. Multiple packages

Multiple packages modelled in the form of an array must be sub-critical, with the package array surrounded on all sides by a 20 cm layer of water.

3.2.1. Array of undamaged packages

The configuration studied is an infinite array of undamaged packages (cylindrical model). Total reflection conditions are applied to all surfaces of the package.

The space between the cavity and the shell is:

- either full of water: the package is also filled with water,
- or filled with vacuum: differential draining of the package.

3.2.2. Array of damaged packages

An array of 2N damaged packages, in contact, is modelled under ACT (Paragraph 685 of Reference <1>).

A reflector of 20 cm of water at the periphery of the array is taken into account.

In this configuration two variants are analysed:

- The interior of the shell is empty, the fuel is moderated: differential draining.
- the interior of the shell is full of water, the fuel is moderated.

3.3. Package modelling

The undamaged package is modelled by a cylindrical shell of [redacted] mm in diameter. The damaged package is modelled by a rectangular shell of [redacted] x [redacted] mm with an unchanged neutron cavity.

Using a conservative approach, the bounding dimensions of the rods are applied in the calculations, i.e. the maximum radius of the UO_2 pellets and the minimum outside radius of the zirconium alloy claddings.

The sensitivity study in reference document <2> defines these parameters as being conservative for the criticality-safety studies.

3.4. Modelling of resin

In accordance with the results of the tests reported in Appendix 2.2-4, the model adopted for the resin in accidental conditions of transport is as follows:

- [redacted] % boron loss through the whole thickness,
- [redacted] % hydrogen loss over [redacted] mm at the external surface.

4. Analysis of packaging loaded with assembly types 15x15, 17x17, 16x16 and 18x18

The criticality-safety study described in Appendix 2.5-1 serves to verify compliance with criticality-safety criteria of the **FCC3 packaging version 1 (Version 100 and 200), the FCC4 packaging version 1.a (Version 400 and 600) or 1.b (Version 600) and the FCC4 packaging version 2 (Version 500)** for the transport of fresh UO2 fuel assembly types:

- 15x15 with [redacted] % ^{235}U enrichment transported in the FCC3 packaging version 1,
- 17x17 12-foot, with [redacted] % ^{235}U enrichment transported in the FCC3 packaging version 1,
- 17x17 XL with [redacted] % ^{235}U enrichment transported in FCC4 packaging version 1.a and FCC4 packaging version 1.b, This study is applicable to 17x17 XLR assemblies (where only the altitude of the grids changes from the 17x17 XL assembly) and GAIA assemblies. In fact, as shown in Chapter 1.3, the small differences between the 17x17 XL and 17x17 GAIA assemblies (mainly due to the external diameters of the guide tubes and instrumentation tubes) have no significant impact on the criticality-safety of the package model. The increase in these diameters has a tendency to reduce the moderating ratio, and therefore reactivity. Studies involving 17x17 XL assemblies therefore cover GAIA assemblies. Moreover, to assure conservatism, the guide tubes are replaced by water during the study. Thus, throughout the criticality study covered in this chapter, the justifications for the 17x17 XL assemblies are equally valid for 17x17 XLR & GAIA assemblies.
- 17x17 EPR with [redacted] % ^{235}U enrichment transported in FCC4 packaging version 1.b,
- 16x16 with [redacted] % ^{235}U enrichment transported in the FCC4 packaging version 2,
- 18x18 with [redacted] % ^{235}U enrichment transported in the FCC4 packaging version 2,

having the following principal characteristics:

- Density 10.96 g/cm^3 (100 % of the theoretical density),
- Complete assemblies: any missing UO2 rods must be replaced by gadolinium-bearing rods, rods containing depleted uranium or a metallic material, or solid metallic bars (materials such as graphite and beryllium are strictly excluded) to avoid increasing assembly moderation levels; the presence of neutron-absorbing poisons in the metal bars is permitted; glycerine may be present up to a content of 5 g max within the assemblies;
- The uranium may originate from reprocessing as the ^{234}U and the ^{236}U present in enriched reprocessed uranium (ERU) are poisons which reduce the reactivity of the assemblies,
- the pellets may contain capturing compounds (chromium oxide for example); their positive influence in terms of margins is disregarded.
- The rods cladding material may include a chrome thickness (in excess thickness or not onto the zirconium alloy), neutron absorbing material which leads to reduced the reactivity,
- If the cladding has an excess thickness of chrome, the moderating ratio into the assembly is reduced, which leads to a reduction of the reactivity.

The packages may only contain one or two assemblies of the same type and having a maximum enrichment of:

- [redacted] % ^{235}U for arrays of 15x15, 17x17 12-foot, 17x17 XL, XLR, GAIA and 17x17 EPR assemblies,
- [redacted] % ^{235}U for arrays of 16x16 and 18x18 assemblies.

The calculations are performed taking into account an expansion of the array over a third of its length, this being a bounding value resulting from the conclusions of the regulatory tests presented in Chapter 2.1. Differential slippage of the rods is analysed and has no significant impact on the reactivity of the rods. The maximum number of packages considered in the case of an array of packages is given in the following table for the different assembly types:

Assembly % U^{235}	Number of rods per assembly	Packaging	Cavity cross-section (mm x mm)	Number N of packages in the array		CSI
				NCT	ACT	
15 x 15 [redacted] % U^{235}	204	FCC3 V1	[redacted] x [redacted]	Infinite	80	0.625
17 x 17 - 12-foot [redacted] % U^{235}	264			Infinite	80	0.625
17 x 17 XL, XLR & GAIA [redacted] % U^{235}	264	FCC4 V1.a FCC4 V1.b		Infinite	80	0.625
17 x 17 type EPR [redacted] % U^{235}	265	FCC4 V1.b		Infinite	80	0.625
16 x 16 [redacted] % U^{235}	236	FCC4 V2	[redacted] x [redacted]	Infinite	6	8.33
18 x 18 [redacted] % U^{235}	300			Infinite	6	8.33

The analysis also includes a sensitivity study on neutron cavity misalignment and ejection of pellets (phenomena not observed following the tests representative of NCT and ACT). This sensitivity study considers grouping of the UO_2 mass ejected in the form of a sphere, and remoderation of the assemblies by replacement of the burst rods by water.

The above table takes into account the possibility of pellet ejection with remoderation of the assemblies. From a criticality standpoint, the number of rods per assembly that can eject the totality of their pellets is:

- 10 for assembly types 16x16 and 18x18 transported in FCC4 packaging version 2,
- 10 for assembly types 15x15 and 17x17 12-foot, transported in FCC3 packaging version 1,
- 7 for type 17x17 XL, XLR and GAIA assemblies transported in FCC4 packaging version 1.a and version 1.b,
- 7 for type 17x17 EPR assemblies transported in FCC4 packaging version 1.b.

5. Analysis of packaging loaded with rods in rod boxes or channels

Under certain circumstances it is necessary to transport variable quantities of rods. These rods are transported in boxes, as described in Chapter 1.3 of this Report, which replace the assemblies inside the neutron cavity.

The packagings used to transport the rods are the same as those designed to transport assemblies:

- FCC3 packaging version 1 for the transport of rod types 14x14 "8-foot", 14x14 "10-foot", 15x15 and 17x17 “12-foot”,
- FCC4 packaging version 1 for the transport of rod types 16x16,17x17 XL, XLR & GAIA, 17x17 EPR and 18x18, and also 14x14 "8-foot", 14x14 "10-foot", 15x15 and 17x17 “12-foot”.

In the study presented in Appendix 2.5-2, compliance of the FCC3 packaging version 1 and the FCC4 packaging version 1 with criticality-safety criteria is verified for the transport of fresh UO_2 fuel rods having the following principal characteristics:

- maximum enrichment: [redacted] % U^{235},
- Density 10.96 g/cm^3 (100 % of the theoretical density),
- nominal diameter [redacted] mm or [redacted] mm,
- any length, therefore slippage possible,
- any number of rods.

Any special rods (gadolinium-bearing rods, depleted uranium rods, metal bars, zirconium alloy bars) are covered by the UO_2 rods.

The pellets may contain capturing compounds (chromium oxide for example); their positive influence in terms of margins is disregarded.

The metal or zirconium alloy bars may contain a neutron poison.

The rods cladding material may include a chrome thickness (in excess thickness or not onto the zirconium alloy), neutron absorbing material which leads to reduced the reactivity.

The maximum fissile cross-section, per cavity, for the rods must be [redacted] mm x [redacted] mm.

The model is a 2D modelling scheme. The rod box is not modelled. The radial spacer is modelled either by water or air whichever is the more conservative case. The calculations are performed under optimum moderation conditions. Differential slippage of the rods is analysed and has no significant impact on the reactivity of the rods.

The following results are presented in Appendix 2.5-2:

- K_{eff} max = 0.782 for the package in isolation,
- K_{eff} max = 0.830 for an infinite array of packages.

These results thus indicate a large margin compared with the adopted criteria (0.95 for isolated package and package array).

The number N for transportation of the rods is infinite in NCT and ACT; we therefore have CSI = 0.

Finally, gadolinium-bearing rods with a minimum content of 2 % on a matrix with a maximum uranium-235 enrichment of [redacted] % can be transported irrespective of the number of rods and type of packaging used. These rods have a $K_{infinite}$ value less than 1.0 irrespective of the moderation used.

6. Analysis of packaging loaded with assembly types 14x14 - 8-foot and 14x14 - 10-foot

Fresh UO_2 fuel assemblies are transported in FCC3 packaging version 2 for type 14x14 "8-foot" and 14x14 "10-foot" assemblies.

This study, described in Appendix 2.5-3, serves to ensure compliance of the FCC3 packaging version 2 with criticality-safety criteria for the transport of fresh UO_2 fuel assembly types:

- 14x14 "8-foot" with [redacted] % ^{235}U enrichment,
- 14x14 "10-foot" with [redacted] % ^{235}U enrichment,

having the following principal characteristics:

- Density 10.96 g/cm^3 (100 % of the theoretical density),
- Complete assemblies: any missing UO_2 rods must be replaced by gadolinium-bearing rods, rods containing depleted uranium or a metallic material, or solid metallic bars (materials such as graphite and beryllium are strictly excluded) to avoid increasing assembly moderation levels; the presence of neutron-absorbing poisons in the metal bars is permitted; glycerine may be present up to a content of 5 g max within the assemblies;
- the uranium may originate from reprocessing as the ^{234}U and the ^{236}U present in enriched reprocessed uranium (ERU) are poisons which reduce the reactivity of the assemblies and which are not taken into account in the criticality-safety assessment.
- The rods cladding material may include a chrome thickness (in excess thickness or not onto the zirconium alloy), neutron absorbing material which leads to reduced the reactivity,
- If the cladding has an excess thickness of chrome, the moderating ratio into the assembly is reduced, which leads to a reduction of the reactivity.

The model is a 2D modelling scheme. The cross-section of the neutron cavity is [redacted] x [redacted] (mm x mm) with 2 continuous pad recesses of maximum cross-section [redacted] x [redacted] (mm x mm). The assembly cross-section is considered in 3 configurations:

- non-expanded ([redacted] mm x [redacted] mm),
- expanded to the cross-section of the neutron cavity ([redacted] mm x [redacted] mm),
- expanded to the cross-section of the neutron cavity and in the pad recesses.

The number of rods able to eject pellets is 20 rods.

Differential slippage of the rods has no significant impact on the reactivity of the rods. Longitudinal wedging of the assemblies is not necessary from the criticality standpoint.

The transportation of assemblies equipped with control clusters is covered by this study as the control clusters contribute a neutron-absorbing material within the assembly while reducing the moderation of the assemblies.

The number N for the transportation of 14x14 8-foot and 14x14 10-foot assemblies is infinite in Normal Conditions of Transport (NCT) and in Accidental Conditions of Transport (ACT); giving us a CSI of 0.

7. Analysis of the increase in the cross section of the cavity

Appendix 2.5-5 studies the impact of an increase in the cross section of the cavity when transporting fuel assemblies. The calculations are carried out with the FCC4 Version 1 packaging.The results of this study are also applicable to the FCC3 Version 1 packaging insofar as the FCC4 Version 1 is identical to the FCC3 Version 1 apart from the longer cavity. This appendix only covers FCC3 Version 1 and FCC4 Version 1 packagings.

7.1. Loading of the fuel assemblies

This impact study is carried out for a 17x17 XL or 17x17 EPR assembly, with a [redacted]% ^{235}U enrichment level, loaded into an FCC4 Version 1 packaging. The study is carried out for a [redacted] array of packages (N=80) under accidental conditions (conditions leading to the maximum reactivity, as detailed in Appendix 2.5-1). The document in reference <3> shows that this modelling of the multiple packages in a [redacted] array leads to obtain a $K_{eff\ max}$ statistically equivalent.

The cavity is modelled with dimensions of [redacted] x [redacted] mm. The other dimensional parameters of the packaging (thickness of plates and resin, lengths, shells, etc.) are unchanged. The assemblies are expanded to a third of their height, up to the cavity wall. The other modelling assumptions are identical to those of Appendix 2.5-1.

Thus, under regulatory transport conditions, the increase in the reactivity of an array of packages, taking into account the increase in cavity section to [redacted] x [redacted] mm (or an increase of 2.3%) and assemblies covering a third of its height, up to the wall of the cavity, is between 700 and 800 pcm, which does not bring into question the respect for the usually applied criticality-safety criteria. The maximum reactivity for fuel assemblies loaded into a FCC3 Version 1 and FCC4 Version 1 packaging is 0.950, all uncertainties included, for a criterion of 0.95, therefore the result of this impact study can be extended to assemblies transported in FCC3 Version 1 or FCC4 Version 1 packagings. As explained in Paragraph 4, these results are also applicable to the transport of 17x17 XLR and GAIA assemblies.

7.2. Loading of non-assembled fuel rods

The impact study in Appendix 2.5-4 is completed for non-assembled fuel rods of [redacted] mm in diameter (most conservative case dealt with in Appendix 2.5-2, loaded into an FCC Version 1 packaging). This study is carried out for an array of packages under accidental conditions (conditions creating the maximum reactivity in Appendix 2.5-2).

The cavity is modelled with dimensions of [redacted] x [redacted] mm. The other dimensional parameters of the packaging (thickness of plates and resin, lengths, shells, etc.) are unchanged. The fuel rods fill the available space minus the thickness of the spacer - or, [redacted] x [redacted] mm (assuming a cavity cross section of [redacted]x[redacted] mm). The other modelling assumptions are identical to those of Appendix 2.5-2.

Thus, under regulatory transport conditions, the increase in the reactivity of the infinite grid of packages, taking into account the increased cavity cross section (to [redacted]x[redacted] mm) and with fuel rods at optimal moderation within a section of [redacted]x[redacted] mm (an increase of 3.6 %), is in the order of 600 pcm, but does not bring into question any of the usually applied criticality-safety criteria. The maximum reactivity for non-assembled rods loaded into a FCC3 Version 1 and FCC4 Version 1 packaging is 0.830, all uncertainties included, for a criterion of 0.95, therefore the result of this impact study can be extended to non-assembled rods transported in FCC3 Version 1 or FCC4 Version 1 packagings.

8. Analysis of the possible presence of glycerine

Assuming 5g of glycerine divided among 264 rods and over the length of the 900 MWe ([redacted] mm) rod, the thickness of the glycerine around the rods is equal to [redacted] mm, which is negligible. This conclusion is also valid for PWR 15x15 and PWR 14x14 assemblies, in fact, assuming the glycerine divided among 179 x 14x14 PWR fuel rods (which covers the case of 15x15 PWR rods) this thickness is [redacted] mm, which is in the same order of magnitude as the 17x17 PWR assemblies. As an indication, in terms of the 17x17 PWR assemblies, even assuming a conservative length of [redacted] mm, corresponding to a 17x17 assembly grid, the depth remains negligible ([redacted] mm).

In addition, glycerine contains less hydrogen than water (the chemical composition of glycerine being $C_3H_8O_3$, with a hydrogen content of 6.59×10^{22} atoms per cm^3, which is lower than that of hydrogen in water (6.69×10^{22} atoms per cm^3).

Finally, glycerine is soluble in water.

As a consequence, assuming the three points covered above, the presence of 5g of glycerine will have no impact on the conclusions of the criticality-safety study undertaken within this chapter.

9. Analysis of the impact of the presence of smooth-walled dummies and EPR assembly model

As the smooth-walled dummy and the EPR model are free of fissile materials and are made up of an inert material (stainless steel and/or tungsten carbide) there is a decrease in the reactivity of the package with regard to the calculated configurations containing fuel assemblies.

The presence of a smooth-walled dummy or model has no impact on the aforementioned demonstrations of criticality-safety.

10. Analysis of the impact of damage on the door for the internal fittings in FCC3 and FCC4 packagings, after a 1m drop onto a bar at the maximum temperature reached during NCT

During the drop on to a bar, the bar perforates the outer shell to impact on the door of the packaging, without piercing it. The assembly is therefore subjected to deformation during the drop onto a bar, caused by the deformation of the door.

The slight additional deformation of the door will have the consequence of creating a localised reduction in the cross-section of the cavity, which will have no impact on the criticality-safety studies (moreover, the conservative conditions, in terms of the criticality-safety modelling, correspond to a maximum cavity size with regard to the possible phenomenon of expansion of the array of rods and not to an indentation causing a reduction in the fissile cross-section and therefore a decrease in the reactivity of the package).

11. Analysis of the impact of a chrome thickness (in excess thickness or not) onto the rods cladding zirconium alloy

Chrome is a neutron absorbing, its presence onto the rods cladding has no impact on the aforementioned demonstrations of criticality-safety.

The same applies in the case of excess thickness of chrome around the cladding, which reduced the moderation ratio of the assembly.

12. Conclusion

Criticality-safety is ensured for the FCC3 and FCC4 packagings loaded with assembly types 15x15, 17x17 12-foot, 17x17 XL, XLR and GAIA, 17x17 EPR, with a CSI = 0.625.

Criticality-safety is ensured for the FCC3 and FCC4 packagings loaded with assembly types 16x16 and 18x18, with a CSI = 8.33.

Criticality-safety is ensured for the FCC3 and FCC4 packagings loaded with type 14x14 assemblies, with a CSI = 0.

Criticality-safety is ensured for the FCC3 and FCC4 packagings loaded with non-assembled fuel rods in boxes, with a CSI = 0.

Finally, gadolinium-bearing rods with a minimum content of 2 % on a matrix with a maximum U^{235} enrichment of [redacted] % can be transported irrespective of the number of rods and type of packaging used. These rods have a $K_{infinite}$ value less than 1.0 irrespective of the moderation used.

Respect for the criticality-safety criteria of the FCC4 Version 1 and FCC3 Version 1 packagings, loaded with non-assembled rods or fuel assembles, is not brought into question for cavity cross sections of up to [redacted] mm x [redacted] mm.

The presence of glycerine (max. 5 g) does not make any difference to the conclusions of the criticality-safety analyses.

The presence of a smooth-walled dummy or EPR assembly model does not make any difference to the conclusions of the criticality-safety analyses.

The presence of chrome localized on rods cladding (in excess thickness or not onto the zirconium alloy), does not make any difference to the conclusions of the criticality-safety analyses.

13. References

<1> Regulations for the Safe Transport of Radioactive Materials - at the revision indicated in Chapter 1.2.

<2> Transnucléaire document 5532-B-2 Ver. 1 – "Envelope geometry for PWR and BWR fuel rods for criticality-safety studies".

<3> Framatome document FS1-0039573EN Rev. 1.0 – « Safety Criticality analysis FCC4 Fuel shipping casks Study of an array of [redacted] damaged packages under Accident Conditions of Transport »

14. List of criticality safety appendices

Appendix	Title	Number of pages
2.5-1	Framatome document – FFDC 00817 rev. 4.0 “Criticality-safety analysis of FCC3 and FCC4 containers – Assembly types 15x15 and 17x17 – Assembly types 17x17 XL, 17x17 EPR,16x16 and 18x18”	2+37
2.5-2	Framatome document – FFDC 01046 rev. 3.0 "Criticality-safety analysis of FCC3 and FCC4 containers – Transport of rods in boxes"	2+33
2.5-3	AREVA NP document – FFDC 01106 rev. A “Criticality-safety analysis of FCC3 containers version 2 – Assembly types 14x14 8-foot and 14x14 10-foot"	2+27
2.5-4	Memo AREVA NP - FF DC 04191 Revision B “Criticality-safety analysis of FCC4 containers - Assembly types 17x17 XL - justification for increase in cavity cross section”	2+7
2.5-5	AREVA NP document – FS1 0012857 rev. 1 “Criticality-safety analysis of FCC4 containers - Justification of the increase in cavity cross-section”	2+5
2.5-6	AREVA NP document – FFDC 00561 rev. 4 “Criticality-safety analysis - Transport packages for fresh UO2 fuels. Determination of uncertainties to be applied to criticality studies performed with CRISTAL”.	2+14
TOTAL		**135**