Proceedings of the 19th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2019
August 4-9, 2019, New Orleans, LA, USA

CRITICALITY STUDIES FOR TRANSPORTATION OF NON-IRRADIATED URANIUM BY AIR IN A NEW TYPE B PACKAGE

Johann DANAN
CEA – France - Cadarache
Department of Radioactive
Materials Transportation (STMR)

ABSTRACT

In application of art.683 of IAEA SSR-6 2018 edition, for packages to be transported by air, the package shall be subcritical under conditions consistent with the Type C package tests assuming reflection by at least 20 cm of water but no water in-leakage.
Where the condition of the package following the tests cannot be demonstrated, worst case assumptions regarding the geometric arrangement of the package and the contents should be made, taking into account all moderating and structural components of the packaging and the package.

As part of a new type B package design, the CEA is conducting criticality studies about air transportation of non-irradiated uranium taking into account a totally ruined package.

These criticality safety analyses are performed to determine the reactivity effect of different modeling assumptions.

This paper will provide an overview of these criticality studies and the most relevant results will be discussed.

I- INTRODUCTION

The French Alternative Energies and Atomic Energy Commission (CEA) is developing a new type B package to replace the TN-BGC 1 package in the coming years.

This new concept currently named “TN-BGC 2” designed to hold the same type of contents as those currently approved for the TN-BGC 1. The TN-BGC 2 will therefore be used to transport fissile material between research reactors and laboratories. This package will be transported by road, sea and air in France or abroad. For air transportation, the contents will be limited to non-irradiated uranium.

In application of Article 683 of IAEA SSR-6 (2018 version) for packages to be transported by air, the package must be subcritical under conditions consistent with the Type C package tests assuming reflection by at least 20 cm of water but no water in-leakage.

The “TN-BGC 2” will not be subjected to type C test sequences. Consequently, we focused on a totally damaged package in our criticality studies. The purpose of this work is to describe the calculation models applied in TN-BGC 2 criticality studies for air transportation. The most relevant results for enriched uranium will also be presented.

II- DESCRIPTION OF THE “TN-BGC 2” PACKAGE

The TN-BGC 2 consists of a cylindrical body with two shocks absorbers at each end. It is equipped with handling devices; one attached to the body and another incorporated into the lower shock absorber. The TN-BGC 2 is shown below in Figure 1.

The cavity is formed by a stainless steel shell. A second stainless steel shell forms the outer envelope of the body. The space between the two shells is filled by a neutron shield resin material containing boron. The cavity is closed by a stainless steel lid. The shocks absorbers are made of balsa wood covered by a stainless steel plate. The shocks absorbers are fixed to the packaging body by screws.

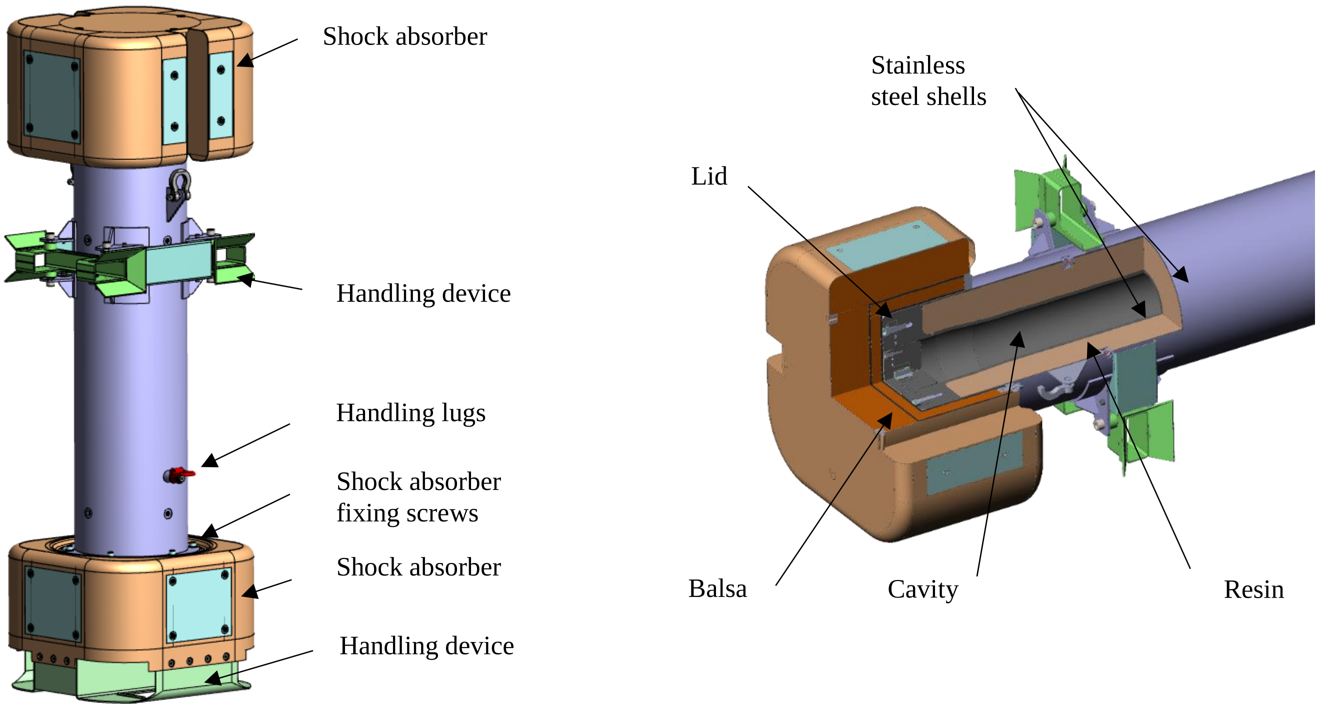


Figure 1: Presentation of the “TN-BGC 2” package

The main characteristics of the package are:

- Height of package: 1949 mm
- Cross section of shock absorber: 600 x 600 mm²
- Maximum mass: 600 kg
- Internal cavity height: 1475 mm
- Internal cavity diameter: 140 mm in current part (152 mm at the top)
- Transportable maximum mass: 100 kg

III- AIR TRANSPORT REGULATIONS

In application of Article 683 of IAEA SSR-6 (2018 version) for packages to be transported by air, the package must be subcritical under conditions consistent with Type C package tests specified in paragraph 734, assuming a reflection by at least 20 cm of water but no water in-leakage.

Paragraph 734 stipulates that the specimen must undergo the following test sequences:

- (a) The tests specified in this order:
    - Paragraph 727(a) – 9-meter free drop onto an unyielding target (type B mechanical test)
    - Paragraph 727(c) – 500 kg object dropped from 9 m onto the specimen (type B mechanical test)
    - Paragraph 735 – type C puncture – tearing test
    - Paragraph 736 – type C thermal test.
- (b) The test specified in paragraph 737 – Type C impact test.

The type C tests are summarized in the following paragraph. For the type C puncture tearing test, the specimen must be dropped onto a 20 cm diameter cylindrical bar with the striking end forming the frustum of a right circular cone. The height of the drop must be 3 m. The type C thermal test conditions are the same than those retained for type B package, except that exposure to the thermal environment must last for a period of 60 min. For the type C impact test, the specimen must be subject to an impact on a unyielding target at a velocity of no less than 90 m/s, at an orientation as to provoke maximum damage.

The transport regulations do not require the same specimen to be subjected to all the prescribed tests because no actual accident sequence combines all the tests at their maximum severity. Thus, separate specimens are allowed to be used for the sequence in 734 (a) and for test in 734 (b).

IV- DESCRIPTION OF THE CALCULATION MODELS

The “TN-BGC 2” is not designed to withstand the tests described above. Consequently, conservative assumptions have to be applied in criticality studies to model the package and its contents according to Specific Safety Guide No. SSG-26 [5]. For this reason, two calculation models were chosen for our criticality studies:

- The first model represents the package and its contents after the test sequence specified in paragraph 734 (a)
- The second model represents the package and its contents after the test in paragraph 734 (b).

The “TN-BGC 2” shock absorbers are not designed to resist an all engulfing fire of 800°C for 60 minutes. When heated, the fusible plugs located on the shocks absorbers will melt and the balsa wood will be consumed. In the first calculation model, the shock absorber wood was assumed to be completely carbonized and the neutron shield resin material was missing. Although the package geometry would not be strongly impacted by the test sequence, we considered a totally damaged package in the criticality studies. Consequently, the calculation model is based on several concentric spheres. In the first model, the carbon in the wood was considered as a reflector around the fissile material.

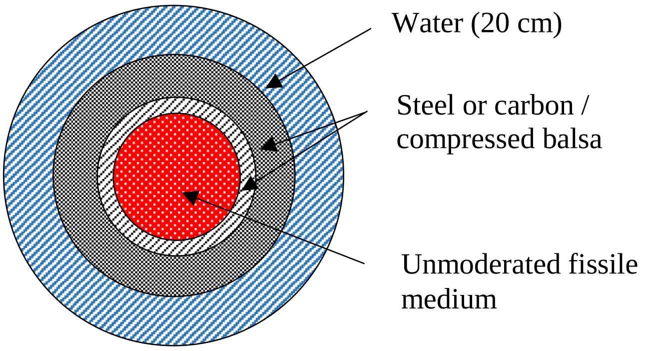
The “TN-BGC 2” is not designed to resist to an impact on an unyielding target at a velocity of 90 m/s. Although it is not possible to predict the mechanical behavior of the package after this test, two scenarios can be considered:

- Disintegration of the package: the different parts of the package including the block of balsa wood forming part of the shock absorbers would break up in all directions. Part of the fissile material would probably be released from the containment system. This scenario is not modeled in our criticality studies. In this scenario, the geometry of the fissile material and the reflection conditions are not optimal.
- Compression of the shocks absorbers: the balsa wood located in the shocks absorbers will absorb part of the impact energy by self-compression. This scenario is modeled in our criticality studies by considering the compressed wood as a reflector around the fissile material. Similarly to the first model, the following conservative assumptions were applied in the second model: the package is also totally destroyed and the neutron shield resin material is still missing.

The two calculation models are based on several concentric spheres reflected by 20 cm of water.

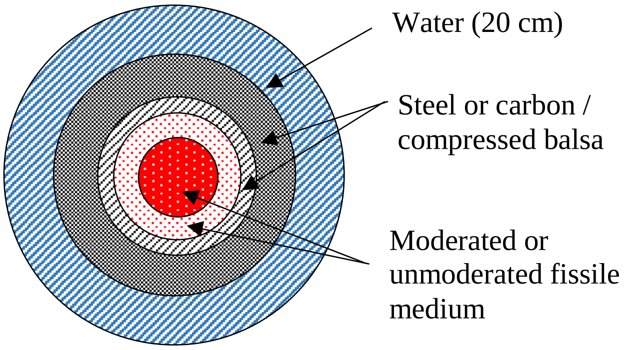
When there is no moderator material in the content:

- The inner sphere contains the fissile medium
- The outer spheres contain the reflector materials: steel of the package and internal fittings and carbon in the wood for the first model, or compressed wood for the second model.



When there are moderator materials in the content:

- The two inner spheres contain all of the fissile material distributed between them. One of the two spheres is moderated by water or CH2 when the moderated material is more hydrogenated than water.
- The outer spheres contain the reflector materials: steel of the package and internal fittings and carbon in the wood for the first model, or compressed wood for the second model.



Wood is a hygroscopic material made of water and dry matter. The amount of water in the wood (moisture content) is expressed as a percentage of the weight of the water compared with its dry weight.

$$mositure\ level\ (\%) = \frac{weight\ of\ wood - ovendry\ weight\ of\ wood}{ovendry\ weight\ of\ wood} \times 100$$

The elementary composition of dry wood is almost the same for all of wood species, i.e. approximately 50% carbon, 42% oxygen, 6% hydrogen, 1% nitrogen, and 1% other elements (calcium, potassium, sodium, etc.) by weight [1].

In the first model, only the carbon elements of the balsa are taken into account with a conservative density of 2.3 g/cm^3.

In the second model, the density of the compressed wood is 1.5 g/cm^3. This density corresponds to a compression ratio of 92% for balsa wood with a density of 0.12. This compression ratio is higher than those observed in wood compression tests conducted by the CEA [2]. Variations of dry wood composition and moisture level were studied for model No.2.

The use of internal fittings made of aluminum (in place of steel) was studied.

V- FISSILE MEDIA AND REFLECTOR MATERIAL

Calculations were performed for three fissile media:

- 100% enriched uranium metal without any moderation
- 100% enriched uranium metal moderated by 500 g of water
- 30 % enriched uranium metal without any moderation.

The following non-fissile materials were used as reflectors in the calculations: steel, aluminum, carbon, compressed balsa, and water. There compositions are detailed in Appendix A.

VI- CALCULATION CODES

Calculations were performed using APOLLO2 – MORET5, which is one of the “standard” channels of the CRISTAL V2.0 package [3][2]. In this study, APOLLO2 (V2.8.3.C) was used with the CEA V5.1.2 nuclear data library (derived from the JEF3.1 evaluation) with 281 energy groups. The MORET 5 code is software designed to simulate the transport of neutrons in three dimensions by means of the Monte Carlo method using fluxes and cross sections generated by Apollo 2 to compute the k_{eff} and output data.

The APOLLO2 – MORET5 qualification report contains data on all relevant materials [4]. Good agreement between the experimental and calculation results was obtained for moderated and unmoderated highly enriched uranium and intermediate-enriched uranium reflected by carbon or aluminum. For stainless steel, the validation report shows an overestimation of the k_{eff}. Consequently, the following criticality acceptance criteria was considered: $k_{eff} + 3\sigma \leq 0{,}95$.

VII- RESULTS

The aim of this study was to determine the maximum allowable mass of fissile media in the TN-BGC 2 for air transportation.

The volume of balsa wood in the shocks absorbers is less than 160,000 cm^3 and its maximum density is 0.12 g/cm^3. For these reasons, a balsa mass of 19.2 kg was considered.

The conservative mass of steel in the package and internal fittings taken into account in the calculations was 440 kg.

In the first model (when the fissile media is reflected by the carbon in the wood), a moisture level of 0% and 60 wt% of carbon in the dry wood was considered conservatively to maximize the amount of carbon as a reflector. Therefore, 11.52 kg of carbon was considered.

In the second model (when the fissile media is reflected by compressed balsa), a moisture level of 12% was taken into account with the following dry wood composition: 50% carbon, 43% oxygen, 6% hydrogen, 1% nitrogen by weight.

The maximum allowable masses of fissile media are given in the table below for the two calculation models. The reflector combinations indicated in this table are those that produce maximum reactivity.

Table 1: Maximum allowable masses of fissile media in the TN-BGC 2 for air transportation

Configuration	Fissile medium	Combination of reflectors (in this order)	Mass of uranium	$k_{eff} + 3\sigma$
Model No. 1 *Reflection by carbon*	^{235}U	Carbon + 20 cm of water	12 kg	0.950
Model No.2 *Reflection by compressed balsa*		Compressed wood + steel + 20 cm of water	13.5 kg	0.946
Model No.1 *Reflection by carbon*	^{235}U moderated by 500 g of water	Carbon + 20 cm of water	10.4 kg	0.949
Model No.2 *Reflection by compressed balsa*		Compressed wood + steel + 20 cm of water	12 kg	0.950
Model No.1 *Reflection by carbon*	30% enriched uranium metal	Carbon + 20 cm of water	90 kg	0.947
Model No.2 *Reflection by compressed balsa*		Compressed wood + steel + 20 cm of water	88 kg	0.949

For 100% enriched uranium metal with or without moderation, the results highlight the fact that the most penalizing model is No.1 when the carbon in the wood is considered as a reflector with a density of 2.3 g/cm^3. The most reactive configuration is obtained with 20 cm of water around the carbon. Steel as a reflector (between the carbon and the 20 cm of water) leads to a slight decrease in the k_{eff}. For moderated uranium, penalizing configurations were obtained when the inner sphere was composed of unmoderated uranium and the second sphere was composed of moderated uranium.

For 30% enriched uranium metal, the results show that the most penalizing model is No. 2 when compressed balsa is considered as a reflector with a density of 1.5 g/cm^3. The most reactive configuration was obtained with steel and 20 cm of water as the reflectors.

Sensitivity analysis of the dry wood composition

The aim of the following calculations was to assess the effect on k_{eff} resulting from changing the dry wood composition. As shown in the table below, the percentage of carbon in dry wood ranges from 50% to 60% and the percentage of hydrogen from 6% to 7%. The fraction of oxygen and nitrogen and the moisture level (12%) does not change. This study was only performed for the second model when the fissile media was reflected by compressed wood. The table below shows the difference in reactivity (pcm, per cent mille) between the configuration modeled with a given composition of dry wood and the configuration modeled with the reference composition (50% carbon, 43% oxygen, 6% hydrogen, and 1% nitrogen by weight).

Table 2: Δk_{eff} in pcm (k_{eff} with the given dry wood composition – k_{eff} with the dry wood reference composition)

		^{235}U (13.5 kg of U)			**^{235}U moderated by 500 g water (12 kg of U)**			**30% enriched uranium metal (88 kg of U)**		
		% of Hydrogen in dry wood								
		6.0%	6.5%	7.0%	6.0%	6.5%	7.0%	6.0%	6.5%	7.0%
% of carbon in dry wood	50.0%	-	277	413	-	30	159	-	11	-27
	55.0%	209	420	486	28	128	257	176	-64	75
	60.0%	539	613	517	325	365	423	-37	237	185

For 100% enriched uranium metal, the results show that the higher the percentage of hydrogen and the percentage of carbon, the higher the k_{eff}. For 30% enriched uranium, the differences in k_{eff} were included in the uncertainty calculation. Therefore, the critical mass determined in Table 1 (88 kg) for model No.2 remained unchanged.

The maximum allowable mass has been conservatively recalculated in Table 4 for 100% enriched uranium with the following composition of dry wood: 60% carbon, 32 % oxygen, 7% hydrogen, and 1% nitrogen by weight. These masses are still greater than the maximum allowable masses of ^{235}U obtained for model No.1 in Table 1.

Table 3: Maximum allowable masses of ^{235}U for compressed wood as reflector (60% carbon, 32% oxygen, 7% hydrogen, and 1% nitrogen by weight in dry wood)

Configuration	**Fissile medium**	**Combination of reflectors**	**Mass of uranium**	**$k_{eff} + 3\sigma$**
Model No. 2 *Reflection by compressed balsa*	^{235}U	Compressed wood + steel + 20 cm of water	13.25 kg	0.948
	^{235}U moderated by 500 g of water	Compressed wood + steel + 20 cm of water	11.7 kg	0.949

Sensitivity analysis of the moisture level

The aim of the following calculations was to evaluate the effect on k_{eff} resulting from changing the amount of water in the wood. The following composition of dry wood was considered in a conservative manner: 60% carbon, 32 % oxygen, 7% hydrogen, and 1% nitrogen by weight. As shown in the table below, the moisture level ranges from 0 % to 20 %. The table below presents the difference in reactivity (in pcm) between the configuration modeled with a given moisture level and the configuration modeled with a 12%

moisture level. This study was only performed for the second model when the fissile material was reflected by compressed wood.

Table 4: Δk_{eff} in pcm (k_{eff} with the given moisture level – k_{eff} with a 12% moisture level)

	Mass of U	Moisture level of balsa							
		0.0%	5.0%	10.0%	12.0%	14.0%	16.0%	18.0%	20.0%
^{235}U	13.25 kg	34	167	-70	-	-113	34	10	-31
^{235}U moderated by 500 g of water	11.75 kg	142	-8	58	-	10	-125	172	-211
30% enriched uranium metal	88 kg	86	-50	-69	-	-115	-47	-239	-312

The differences in k_{eff} were included in the uncertainty calculation for all three fissile media. The variation in the moisture level of balsa had no effect on the k_{eff}. Therefore, the maximum allowable masses calculated in Table 2 and 4 remain unchanged.

Use of internal fittings in aluminum

The aim of the following calculations was to determine the effect on k_{eff} resulting from using internal fittings made of aluminum. A mass of 30 kg of aluminum was considered in the calculations. The mass of steel was then reduced to 410 kg.

For the first model, the most reactive configuration was obtained without aluminum and steel (with 20 cm of water around the carbon). Aluminum and steel as a reflector leads to a slight decrease in the k_{eff}. Therefore, the maximum allowable masses calculated in Table 1 for the first model remains unchanged.

The table below presents the results for the second model. The following composition of dry wood was considered: 60% carbon, 32% oxygen, 7% hydrogen, and 1% nitrogen by weight. The moisture level of the wood was 12%. The reflector combinations indicated in this table are those producing maximum reactivity.

Table 5: k_{eff} comparison with internal fittings made of aluminum

Configuration	Fissile medium	Internal fitting material	Combination of reflectors (in this order)	Mass of uranium	$k_{eff} + 3\sigma$
Model No. 2 *Reflection by compressed wood*	^{235}U	Aluminum	Compressed wood + steel (410 kg) + aluminum (30 kg) + 20 cm of water	13.25 kg	0.950
		steel	Compressed wood + steel (440 kg) + 20 cm of water		0.948
	^{235}U moderated by 500 g of water	Aluminum	Carbon + aluminum+ 20 cm of water	11.7 kg	0.949
		steel	Compressed wood + steel (440 kg) + 20 cm of water		0.949
	30% enriched uranium metal	Aluminum	Compressed wood + steel (410 kg) + aluminum (30 kg) + 20 cm of water	88 kg	0.951
		steel	Compressed wood + steel (440 kg) + 20 cm of water		0.951

As shown in the table, the use of internal fittings made of aluminum does not affect the reactivity. Therefore, the maximum allowable masses presented in Table 5 for the second model remain unchanged.

VIII- CONCLUSION

This paper presents and justifies the model assumptions applied in the TN-BGC 2 criticality studies for the air transportation of fissile material. The maximum allowable masses of fissile material calculated in this study are detailed below:

- 12 kg of 100% enriched uranium metal without any moderation
- 10.4 kg of 100% enriched uranium metal moderated by 500 g of water
- 88 kg of 30% enriched uranium metal without any moderation.

Internal fittings made of aluminum or steel can be used. Calculations were performed with the following assumptions:

- Maximum mass of steel and aluminum of the package including its contents: 440 kg
- Maximum mass of aluminum of internal fittings: 30 kg
- Maximum volume of balsa in the shocks absorbers: 160,000 cm^3
- Maximum density of balsa: 0.12 g/cm^3.

Acknowledgements

I would like to thank my colleagues Marine BOUCHER, Thomas CUVILLIER, Thierry DELON, Florian GARCIA and Vincent PAUTROT who are involved in TN-BGC 2 project and who helped me in many ways.

In addition, I am particularly grateful to Sebastien CLAVERIE FORGUES with whom I worked on the design of the scenarios and the assumptions made.

I was also given valuable help by Louis DROUARD who verified my calculations.

References

[1] Technique de l'ingénieur C925v2 : Matériau bois, Structure et caractéristiques - Marie Christine TROUY-TRIBOULOT, Pascal TRIBOULOT

[2] Rapport des essais de compression en température de différentes essences de bois utilisées dans les capots des emballages de transport du CEA – CEA/DSN/STMR/LEPE/EMBAL/ NOT 0007 ind 2

[3] Notice d'identification du formulaire CRISTAL V2.0.1 - CRISTAL V2/N DI-V2.0/A

[4] Contribution à la qualification de la voie standard APOLLO2-MORET 5 du formulaire de criticité CRISTAL - Synthèse des résultats de calcul obtenus avec la version V2.0 du formulaire CRISTAL – Rapport PSN-EXP/SNC/2014-265

[5] Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2012 Edition) - Specific Safety Guide No. SSG-26

APPENDIX A: Reflector material compositions

Reflector	Density ($g.cm^{-3}$)	Atomic composition ($at.barn^{-1}.cm^{-1}$)	
Water	0.998	H1_H2O	6.672E-02
		O	3.336E-02
Steel	7.9	Fe	6.134 E-02
		Cr	1.647 E-02
		Ni	2.588 E-03
Aluminum	2.7	Al27	6.024 E-02
Carbon	2.3	C nat	1.153 E-01
Compressed balsa*	1.5	C nat	3.358 E-02
		H1_H2O	5.876 E-02
		O	2.705 E-02
		N	5.758 E-04

* The composition of compressed balsa varies according to the moisture level and dry wood composition. This composition is valid for a 12% moisture level and the following composition of dry wood: 50% carbon, 43% oxygen, 6% hydrogen, and 1% nitrogen in weight.