LEUPA

Type B(U) Package to Contain Fissile Substances

CRITICALITY ANALYSIS

Made by
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REVISION SHEET		**Document No.:** 0908-LE01-3BEIN-024-C **Revision:** C			
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Revision Letter	**Description of the Revision**	**Prepared**	**Reviewed**	**Approved**	
A	Original	FDS	SBM	JCO	
B	REFERENCE	FDS	SBM	JCO	
C	Added the assessment of an individual package in isolation and Upper Subcritical Limits considerations.	FDS	DFH FA	JCO	

CONTENTS

1 PURPOSE

1. Demonstrate that LEUPA package complies with Argentine Standard AR 10.16.1. Rev. 2 “Transport of Radioactive Materials” for the safe transport by land, by sea or by air of fissile substances indicated in this document.

2 SCOPE

1. This document analyses and demonstrates compliance of LEUPA package with the national regulations for safe transport by land, by sea, or by air of fissile substances indicated in this document, exclusively under the viewpoint of sub-criticality.

3 REFERENCES

[1] ARN. *Transport of Radioactive Materials*. Standard AR 10.16.1. Rev. 2. Argentine Republic: ARN, 2011.

C [2] MCNP – A General N-Particle Transport Code, Version 5 – Volume I: Overview and Theory, X-5 Monte Carlo Team, LA-UR-03-1987, Los Alamos National Laboratory (April, 2003, revised February 2008).

[3] 0908-LE02-3BEIN-008-B, Tests Carried Out On Specimens Of The Design Of Type B(U) Package To Transport Radioactive Material Final Report.

C [4] SSG-26, “Specific Safety Guide”, Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, IAEA, 2012.

[5] 0908-LE01-3BEIN-027-A, Calculation Line for LEUPA Sub-Criticality Analysis.

4 ABBREVIATIONS

Abbreviation	Description
CSI	Criticality Safety Index
k_{eff}	Effective Multiplication Factor
LEUPA	Low Enriched Uranium Package for Transport
SD	Standard Deviation

5 DESCRIPTION

1. The general assembly of LEUPA packaging can be seen in Draw. 0908-LE01-3ASIN-004.
2. The package is composed as follows:
   a. Fissile substances to be transported, packed in polyethylene bags or similar.
   b. The package, which is a single inseparable set with enclosure systems and thermal insulation.

5.1 Fissile Substances

1. The fissile substance to transport consists of some of the following uranium composites, with an enrichment lower than 20%:
   a. Natural uranium.
   b. Uranium metal in granules or pieces.
   c. U_3Si_2 in powder or pieces.

   d. U_xAl_y in powder or pieces.
   e. U_3O_8 in powder.
2. So as to evaluate criticality, a mass of uranium metal of 50 kg is adopted.

5.2 Packaging

5.2.1 Enclosure System

1. The enclosure system is formed by steel non-hermetic vessels called –in the project context– inner cans, filled with fissile substance. Each of them has an inner volume of 1.56 dm^3. LEUPA can load up to four of these inner cans, which in turn are placed in the so called container. This is a container designed according with code ASME Section III, Division 1, Sub-section NB, with an inner usable volume of around 8.25 dm^3. Pressure and temperature values considered in design are of 700 kPa manometric and 70 ºC, respectively. The container is composed of a main body and a standardized flange, both of stainless steel. The flange is fixed to the main body by means of 8 UNC ¾" screws and is sealed by spiral graphite gasket able to work with a limit temperature of up to 450 ºC. The flange has an ergonomic designed folding handle.
2. Rubber supplements eliminate the gap between the inner cans and the container. Their function is to diminish dynamic effects in cases of normal or accident transport.
3. Linked to the container there is a cylindrical stainless steel double wall component. The space between walls (17 mm approximately) is filled with casted high purity cadmium. The flanged cover of the container also has a double wall inside which cadmium is filtered, so that the load of fissile substances is surrounded almost completely by the neutron absorbent material.
4. This assembly forms a compact undeformable central cell.

5.2.2 Remainder of Packaging

1. Outside the described cell, eight (8) stainless steel structural plates are welded radially working as a link between the cell and the outer wall of packaging. Furthermore, the packaging has four angle profile rings one in each end of the packaging and the other two at around one third (1/3) and two thirds (2/3) of the packaging height, respectively, as reinforcement. Each ring is welded to the radial plates, and in turn, these are welded to the central cell, thus forming an integrated unity. The external wall of the packaging is a stainless steel cylinder plate. The packaging has circular covers welded at the ends, which make, together with the external wall and the central cell, a volume where the thermal insulator, by means of gravity filtering is placed; thus, the central cell is surrounded by a thickness of thermal insulator of around 150 mm.
2. The packaging has a removable intermediate cover that is a solid construction made of cylindrical stainless steel plate and circular covers, which, as stated above, make a volume that can be filled with thermal insulator by gravity filtering technique, thus, this volume has a thickness of around 150 mm.
3. The removable intermediate cover is linked to the rest of the packaging by means of 6 M12 screws, with a rubber gasket between both.
4. Outside the removable intermediate cover, there is another cover made exclusively of a stainless steel circular plate, also fixed to the rest of the packaging, by means of 6 M12 screws. Between both there is also a 5 mm rubber gasket to prevent from dirt or humidity.
5. Both, the external and the removable intermediate covers have ergonomic designed folding handles.

6. All elements of the packaging fulfil the function of protection against impacts. It is a unity that can absorb mechanical energy by deformation without losing its thermal protection capacity
7. The thermal insulator used is called in the market Kaolite 1600, a vermiculite cementitious composite in powder that must be prepared mixing it with water, and can be used at 1600 ºF (871 ºC). It may be applied by filtering or by pressure.
8. Its mechanical properties depend on drying conditions.
9. The external cover and the rest of the packaging have pieces that allow an inviolable closure of the package by means of high resistance brass precincts, marked with permanent characters.
10. The packaging has four lifting points formed by standardized shackles with 0.5 ton lifting capacity each, appropriately linked to the upper ring of packaging.

Table 1: LEUPA package description

System	Description
Package	Classification: Type B(U), for transport by land, by sea or by air with fissile substances. ARN Approval Certificate: – Criticality Safety Index: (CSI): 0.69. Useful Load: 50 kg of enriched uranium at 19.75% in U^{235} (limit value). Total Mass of Package: 430 kg. Dimensions: Height 1155 mm, Diameter Ext. 532 mm. Lifting Points: 4 shackles with 500 kg capacity each. Clamping points for Transport: 4.
Contends	Some of the following: a. Natural uranium. b. Uranium metal in grains or pieces. c. U_3Si_2 powder or in pieces. d. U_xAl_y powder or pieces. e. UO_2 powder. f. U_3O_8 powder.
Enclosure System	Building Material: Stainless Steel. Pressure vessel, designed in accordance with code ASME Section III, Division 1, Sub-section NB. Nominal Diameter: ND 125 (5”). Inner Volume: 8.25 dm^3. Design Pressure: 700 kPa (manometric). Test Pressure: 875 kPa (manometric). Design Temperature: 70 ºC. Test Temperature: Ambient (20 ºC). Gasket Type: Spiral, non-reusable made of graphite and stainless steel. It accords with Standard ASME B 16.20. Type of Screws of Sealing of Flange: ASTM A 193 Gr. B7, UNC ¾” 10 HPP. Neutron Absorbent: Approx. 58 kg high purity cadmium, in accordance with Standard ASTM B440 Grade L 01951.

System	Description
Remainder of packaging	Thermal Insulator: Approx. 85 kg of Kaolite 1600. Gaskets: 5 mm thick rubber. Cover Screws: 6 M12 in each cover, type A2-70 ISO 3506-1. Safety Precinct Type: 2 brass precincts, encoded with 6 number digits.

6 MATERIALS USED TO EVALUATE CRITICALITY

1. Table 2 describes all used materials in all performed calculations to ensure sub-criticality of the LEUPA package, under normal and accident conditions. Approximate mass involved and its composition is also detailed.

Table 2: Materials used in criticality evaluations

Material	Aprox. Mass [kg]	Density [g/cm^3]	Element	% Weight
Uranium metal	50.0	18.9	U^{235} U^{238}	19.8 80.1
Polyethylene	0.4	–	H C	14.4 85.6
Kaolite 1600	85	0.405 (without water)	Al_2O_3 SiO_2 Fe_2O_3 TiO_2 CaO MgO Na_2O	11.0 33.0 7.9 1.4 30.0 12.1 4.6
AISI 304 L	244	7.9	Fe Cr Ni Mo Mn Si C	65.47 17.0 12.0 2.5 2.0 1.0 0.03
Cadmium	58	8.65	Cd	100.0

7 QUALIFICATION OF LEUPA PACKAGE FOR THE TRANSPORT OF FISSILE SUBSTANCES

7.1 Sub-criticality Assurance

1. According with the requirements established in paragraph 671 of Reference [1] (as from here on named Standard), related to the assurance of sub-criticality in normal and

accident conditions, calculations were carried out following conditions specified in said Standard.

2. A contingency analysis was also made to show the package sub-criticality under normal and accident conditions (see Table 3).
3. The analysis of assurance of sub-criticality is based on the calculation of the effective multiplication factor, k_{eff}. Several configurations were analysed under conservative models.
4. The Standard requires the assurance of criticality of the individual package in isolation and package arrays in normal and accident conditions.
5. The destructive-accumulative tests specified by the Standard were done and are documented in Reference [3]. Some of the conclusions extracted from those analyses, are show in the following points.
   i. The inner cans that contain the fissile substances and the cadmium chamber retained their original state after the tests.
   ii. The main impact affects only the primary containment, with minor modifications to the external dimensions.
6. In accordance with what previously said, the damaged package is geometrically similar to the package intact. No significance will be considered to the possible variation of the effective multiplication factor due to deformations that might be produced during tests.
7. The difference between an intact package and a damaged one will be the entry of water in all empty spaces of the package, that is to say, interior of inner cans and the spaces between the cadmium chamber and the thermal insulation.
8. Given the uncertainty on how water may go inside the packages, analyses are made varying the density of water in a homogeneous way, with values which may go from 1.0E-7 to 1.0 g/cm^3. In this way the risk of criticality can be analysed associated to the incoming of water in the package related to H/U moderation.

Table 3: Contingencies and contention barriers to assure sub-criticality (as established in paragraph 671 of the Standard)

Contingencies	Individual package	Package array
1. Leakage of water into or out of packages.	i. Sub-criticality of a package isolated, evaluated in Sections 7.4.1.2.2, 7.4.1.2.3 and 7.4.1.2.4	i. Sub-criticality of a set of packages piled up 6x6x4, evaluated in Sections 7.3.2.2 and 7.4.2.2.2, 7.4.2.2.3 and 7.4.2.2.4
2. Loss of efficiency of built-in neutron absorbers or moderators	i. Sub-criticality of a package isolated, evaluated in Sections 7.4.1.2.1. ii. Sub-criticality in the worst conditions analysed in 1 and 2.i, evaluated in Section 7.4.1.2.5	i. Sub-criticality criticality of a set of packages piled up 6x6x4, evaluated in Sections 7.3.2.2 and 7.4.2.2.1 ii. Sub-criticality in the worst conditions analysed in 1 and 2.i, evaluated in Section 7.4.2.2.5.
3. Rearrangement of the contents either within the package or as a result of loss from the package	i. It is supposed that the integrity of the packaging will be kept after the tests specified in Paragraphs 719 to 724 of the Standard. ii. Sub-criticality of a very conservative model described in Section 8.1.1.	
4. Reduction of spaces within or between packages.	i. It is supposed that the integrity of the packaging will be kept after the tests specified in Paragraphs 719 to 724 of the Standard.	

Contingencies	Individual package	Package array
5. Packages becoming immersed in water or buried in snow.	i. Sub-criticality of a package isolated, evaluated in Sections 7.4.1.2.2, 7.4.1.2.3 and 7.4.1.2.4.	i. Sub-criticality of a set of packages piled up in 6x6x4 evaluated in Sections 7.3.2.2 and 7.4.2.2.2, 7.4.2.2.3 and 7.4.2.2.4.
6. Temperature changes.	i. Sub-criticality of a package isolated, evaluated in Sections 7.4.1.2.1	i. Sub-criticality of a set of packages piled up in 6x6x4 evaluated in Section 7.4.2.2.1.

7.2 Models of Used Calculation and Codes

1. The evaluations of the effective multiplication factor were done following the calculation code Monte Carlo MCNP5, version 1.6, internationally known and accepted as appropriate for this type of evaluations (see Reference [2] and [5]).
2. The cross sections of the majority of materials involved in analysis are based on the data library ENDF/B-VII.
3. For each calculation case it is obtained from the MCNP output the effective multiplication factor (k_{eff}) together with its standard deviation (SD). The final results are presented as k_{eff} plus three times the SD, reference [4] and [5].
4. It is verified that the all calculated values for the effective multiplication factor (k_{eff}) are lower than the Upper Subcritical Limit (0.9350) established on Reference [5].
5. Figures 1 and 2 show horizontal and vertical sections of the simulated model in piling up and used as input in the MCNP calculation code.

Figure 1: LEUPA horizontal section showing one of the packages in piling up

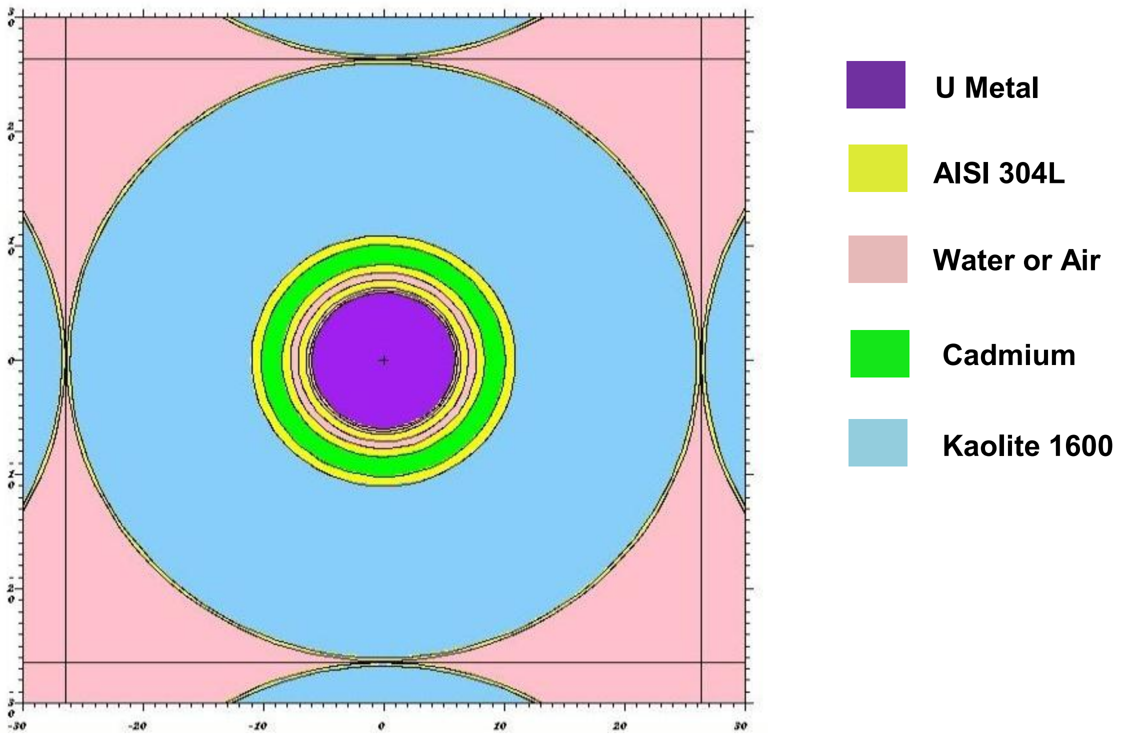
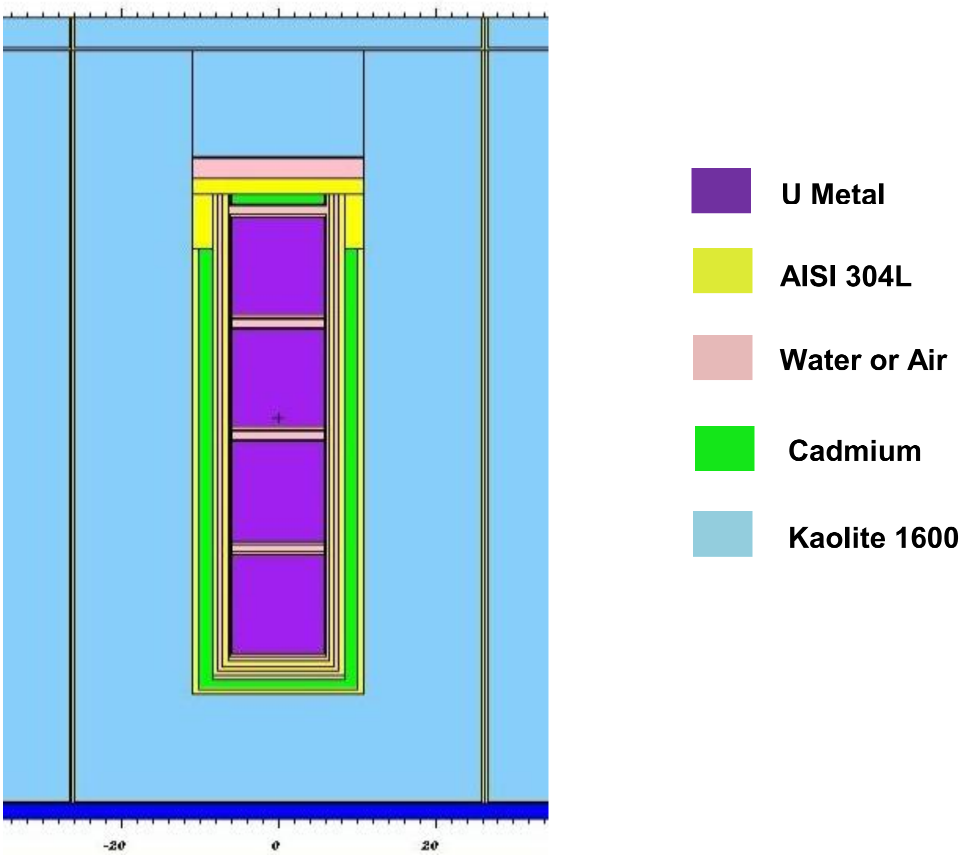


Figure 2: LEUPA vertical section showing one of the packages in piling up



7.3 Description of Analysis

7.3.1 Individual package

1. According to paragraph 677, 678 and 679 of the Standard:

    677. *For a package in isolation, it shall be assumed that water can leak into or out of all void spaces of the package, including those within the containment system.*

    678. *It shall be assumed that the confinement system shall be closely reflected by at least 20 cm of water or such greater reflection as may additionally be provided by the surrounding material of the packaging.*

    679. *The package shall be subcritical under the conditions of paras 677 and 678*

2. As established in section 7.1, it is considered that the damaged package has geometry similar to the intact one.
3. To verify the compliance of paragraph 678 the package is surrounded by 20 cm of water.
4. To verify compliance with paragraph 677, it is considered the entrance of water to the empty spaces of the package. Due to the geometry and materials of the package, there are several possibilities of water coming into the package, which may be considered as abnormal situations:

    a. Variation of quantity of water in the thermal insulator Kaolite 1600:

    i. This material is a cementitious composite prepared by adding water. Most water is retained in the mixture, but proportion is uncertain and depends on ambient conditions.

ii. The quantity of hydrogenated material in the mixture may vary as a consequence of temperature changes due to processes such as drying and ignition.

b. As the worst evaluated case is that, in which the insulation has no hydrogen in the mixture, variation of the multiplication factor with the quantity of water added to the mixtures was studied as “abnormal” cases.
c. Water entering the inner empty spaces of the inner container (that is to say, the inside of the can that contains the mass of uranium metal);
d. Water entering the empty spaces between the inner cans container and the cadmium chamber and into empty spaces between packages (signalled as “water or air” in Figure 1).
e. Combinations of all of the above cases.
f. Abnormal case is an error in manufacturing where cadmium is not filtered in the cadmium chamber.

7.3.2 Package array

1. According with preliminary evaluations, the sub-criticality of an infinite number of packages cannot be assured. Therefore, for analysis a number “N” was considered equivalent to 72 packages piled up in 8x8x6 packages in normal conditions (five times “N”) and in 6x6x4 packages in accident conditions (two times “N”).

7.3.2.1 Normal Conditions

1. According to paragraph 681 of the Standard:

   ***681**. A number N shall be derived, such that five times N packages shall be subcritical for the arrangement and package conditions that provide the maximum neutron multiplication consistent with the following:*

   (a) There shall not be anything between the packages and the package arrangement shall be reflected on all sides by at least 20 cm of water; and

   (b) The state of the packages shall be their assessed or demonstrated condition if they had been subjected to the tests specified in paras 719-724.

2. To verify compliance with paragraph 681, 384 packages were evaluated, piled up 8 x 8 x 6 and the whole set surrounded by 30 cm of water (higher than the 20 cm established in Standard).
3. As indicated in section 7.1, the damaged package is considered to have the same geometry as the intact package.

7.3.2.2 Accident Conditions

1. Following paragraph 682 of the Standard:

   ***682**. A number N shall be derived, such that two times N packages shall be subcritical for the arrangement and package conditions that provide the maximum neutron multiplication consistent with the following:*

   (a) Hydrogenous moderation between the packages and the package arrangement reflected on all sides by at least 20 cm of water; and

   (b) The tests specified in paras 719–724, followed by whichever of the following is the more limiting:

   (i) The tests specified in para. 727(b), and either para. 727(c) for packages having a mass not greater than 500 kg and an overall density not greater

than 1000 kg/m^3 based on the external dimensions, or para. 727(a) for all other packages; followed by the test specified in para. 728 and completed by the tests specified in paras 731–733; or

(ii) The test specified in para. 729; and

(c) Where any part of the fissile material escapes from the containment system following the tests specified in para. 682(b), it shall be assumed that fissile material escapes from each package in the array, and all of the fissile material 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.

2. To verify compliance with paragraph 682, 144 packages shall be evaluated, said packages piled up 6 x 6 x 4 and the whole unity surrounded by 30 cm of water.
3. As established in section 7.1, it is considered that the damaged package has geometry similar to the intact one.
4. Due to the geometry and materials of the package, there are several possibilities of water coming into the piled sets, which may be considered as abnormal situations:
   a. Variation of quantity of water in the thermal insulator Kaolite 1600:
      i. This material is a cementitious composite prepared by adding water. Most water is retained in the mixture, but proportion is uncertain and depends on ambient conditions.
      ii. The quantity of hydrogenated material in the mixture may vary as a consequence of temperature changes due to processes such as drying and ignition.
   b. As the worst evaluated case is that, in which the insulation has no hydrogen in the mixture, variation of the multiplication factor with the quantity of water added to the mixtures was studied as “abnormal” cases.
   c. Water entering the inner empty spaces of the inner container (that is to say, the inside of the can that carries the mass of uranium metal);
   d. Water entering the empty spaces between the inner cans container and the cadmium chamber and into empty spaces between packages (signalled as “water or air” in Figure 1).
   e. Combinations of all of the above cases.
   f. Abnormal case is an error in manufacturing where cadmium is not filtered in the cadmium chamber.

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7.4 Results

7.4.1 Individual package

7.4.1.1 Compliance with Paragraph 678

1. To verify the compliance paragraph 678 the package is surrounded by 20 cm of water:

$$\boxed{k_{eff} + 3\sigma \quad \sigma < 0.00013 \quad = 0.26095}$$

7.4.1.2 Compliance with Paragraph 677

7.4.1.2.1 Content of Water in Thermal Insulator

1. An analysis took place studying several mixtures of Kaolite 1600 and water. The mass of the thermal insulation kept constant at a value of 84.4 kg.

2. Table 4 shows the evaluated cases, the name of the MCNP input file (as a reference), the effective multiplication factor (k_{eff}) obtained together with its standard deviation (SD) and the final result as k_{eff} plus three times the SD.
3. The first column shows the relation between the insulating mass and the water considered in the mixture. For example, 100/0 considers the dry insulator, while a value 100/180 indicates a relation 1.8 between the mass of water and the thermal insulator.
4. The column identified as "# Cycles" is the total number of KCODE cycles done, each of them issuing two thousand five hundred (2500) fission neutrons.

Table 4: Multiplication factor for several water mass

Case	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
100/0	lp-Ind_0050.inp	1500	0.26152	0.00015	0.26197
100/50	lp-Ind_0051.inp	1500	0.27186	0.00016	0.27234
100/100	lp-Ind_0052.inp	1500	0.27554	0.00017	0.27605
100/141	lp-Ind_0053.inp	1500	0.27690	0.00017	0.27741
100/180	lp-Ind_0054.inp	1500	0.27820	0.00017	0.27871
100/250	lp-Ind_0055.inp	1500	0.27935	0.00017	0.27986

5. The most unfavourable situation is the case with the highest amount of water in the thermal insulator.

7.4.1.2.2 Variation of Water Density in Empty Spaces

1. Due to the uncertainty of the way water would enter into packages, several analysis were made in which density of homogenous water was varied, with values which went from 1.0E-7 to 1.0 g/cm^3. Thus, criticality risk can be analysed, associated with the water in the package, as regards the H/U moderation of the package.
2. The thermal insulator was considered without water.
3. Table 5 shows the evaluated cases, the name of the MCNP input file (as reference), and the effective multiplication factor (k_{eff}) obtained together with its SD, and the final result obtained as k_{eff} plus three times SD.
4. The first column shows the density of water in empty spaces. Empty spaces can be seen in Figure 1, indicated as "water or air".
5. The column identified as "# Cycles" is the total number of KCODE cycles done, each of them issuing two thousand five hundred (2500) fission neutrons.
6. The most unfavourable situation is the case with the highest amount of water in the empty spaces.

Table 5: Multiplication factor for several water densities

Density	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
1.E-07	lp-Ind_0001.inp	1500	0.26184	0.00015	0.26229
1.E-05	lp-Ind_0002.inp	1500	0.26026	0.00015	0.26071
1.E-03	lp-Ind_0003.inp	1500	0.26023	0.00015	0.26068
1.E-02	lp-Ind_0004.inp	1500	0.26108	0.00015	0.26153
0.1	lp-Ind_0005.inp	1500	0.27063	0.00016	0.27111

Density	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
0.2	Ip-Ind_0006.inp	1500	0.28237	0.00018	0.28291
0.4	Ip-Ind_0007.inp	1500	0.30778	0.00020	0.30838
0.6	Ip-Ind_0008.inp	1500	0.33346	0.00023	0.33415
0.8	Ip-Ind_0009.inp	1500	0.36020	0.00025	0.36095
1.0	Ip-Ind_0010.inp	1500	0.38562	0.00026	0.38640

7.4.1.2.3 Variation of the Water Mass introduced in Inner Cans

1. The variation of the effective multiplication factor with the adding of different water mass inside the inner cans was studied.
2. The mixture of water and uranium metal was supposed homogenous inside the inner can.
3. The thermal insulator was taken without water.
4. Table 6 shows the cases evaluated, the name of the MCNP input file (as reference), and the effective multiplication factor (k_{eff}) obtained together with its SD, and the final result obtained as k_{eff} plus three times SD.
5. The first column shows the water mass mixed with uranium metal.
6. The column identified as “# Cycles” is the total number of KCODE cycles KCODE, each of them issuing two thousand five hundred (2500) fission neutrons.
7. It can be seen that the multiplication factor grows monotonously with the additional water mass added to the uranium metal, and the worst case is a water mass of 1000 g. Due to the volume the uranium metal takes in the inner can, not more than 900 g of water can be added.

Table 6: Multiplication factor for several water mass mixed with uranium metal

Water Mass [g]	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
100.0	Ip-Ind_0030.inp	2000	0.29279	0.00016	0.29327
200.0	Ip-Ind_0031.inp	2000	0.32923	0.00019	0.32980
300.0	Ip-Ind_0032.inp	2000	0.36688	0.00021	0.36751
400.0	Ip-Ind_0033.inp	2000	0.40442	0.00023	0.40511
500.0	Ip-Ind_0034.inp	2000	0.44340	0.00026	0.44418
600.0	Ip-Ind_0035.inp	2000	0.48062	0.00028	0.48146
700.0	Ip-Ind_0036.inp	2000	0.51727	0.00029	0.51814
800.0	Ip-Ind_0037.inp	2000	0.55291	0.00031	0.55384
900.0	Ip-Ind_0038.inp	2000	0.58831	0.00031	0.58924
1000.0	Ip-Ind_0039.inp	2000	0.62230	0.00034	0.62332

7.4.1.2.4 Variation of Water Mass Introduced simultaneously in Several Compartments

1. The effective multiplication factor was studied when different water masses were added inside the inner cans and the empty spaces and with water caught in the thermal insulation.

2. In a conservative way, it was considered, in all cases, a mixture of 1000 g of water and uranium metal inside the inner can. The mixture was supposed to be homogenous inside the inner can.
3. Table 7 shows the cases evaluated, the name of the MCNP input file (as reference), and the effective multiplication factor (k_{eff}) obtained together with its SD and the final result obtained as k_{eff} plus three times SD.
4. The first column shows the water mass mixed with thermal insulation, keeping the same names as in Table 4
5. The second column is density of water that entered in empty spaces.
6. The column identified as "# Cycles" is the total number of KCODE cycles done, each of them issuing two thousand five hundred (2500) fission neutrons.
7. It can be seen that the worst case is that in which inner cans are flooded with water (1000 g), the thermal insulator full with water (100/180) and the highest density of water in empty spaces.

Table 7: Variation of quantities of water in combined form

Water Mass [g]	Density of water in Empty Spaces	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
100/0	1.E-05	Ip-Ind_0511.inp	2000	0.62324	0.00034	0.62426
	1.E-02	Ip-Ind_0512.inp	2000	0.62455	0.00034	0.62557
	0.3	Ip-Ind_0513.inp	2000	0.64669	0.00034	0.64771
	0.8	Ip-Ind_0514.inp	2000	0.68613	0.00035	0.68718
	1.0	Ip-Ind_0515.inp	2000	0.70102	0.00036	0.70210
100/50	1.E-05	Ip-Ind_0611.inp	2000	0.62956	0.00034	0.63058
	1.E-02	Ip-Ind_0612.inp	2000	0.63046	0.00034	0.63148
	0.3	Ip-Ind_0613.inp	2000	0.65232	0.00034	0.65334
	0.8	Ip-Ind_0614.inp	2000	0.69096	0.00034	0.69198
	1.0	Ip-Ind_0615.inp	2000	0.70471	0.00034	0.70573
100/100	1.E-05	Ip-Ind_0711.inp	2000	0.63231	0.00033	0.63330
	1.E-02	Ip-Ind_0712.inp	2000	0.63249	0.00033	0.63348
	0.3	Ip-Ind_0713.inp	2000	0.65378	0.00034	0.65480
	0.8	Ip-Ind_0714.inp	2000	0.69193	0.00033	0.69292
	1.0	Ip-Ind_0715.inp	2000	0.70580	0.00035	0.70685
100/141 (nominal)	1.E-05	Ip-Ind_0411.inp	2000	0.63246	0.00033	0.63345
	1.E-02	Ip-Ind_0412.inp	2000	0.63270	0.00034	0.63372
	0.3	Ip-Ind_0413.inp	2000	0.65528	0.00034	0.65630
	0.8	Ip-Ind_0414.inp	2000	0.69245	0.00035	0.69350
	1.0	Ip-Ind_0415.inp	2000	0.70607	0.00035	0.70712

Water Mass [g]	Density of water in Empty Spaces	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
100/180	1.E-05	Ip-Ind_0811.inp	2000	0.63343	0.00034	0.63445
	1.E-02	Ip-Ind_0812.inp	2000	0.63384	0.00033	0.63483
	0.3	Ip-Ind_0813.inp	2000	0.6556	0.00034	0.65662
	0.8	Ip-Ind_0814.inp	2000	0.69333	0.00035	0.69438
	1.0	Ip-Ind_0815.inp	2000	0.70700	0.00035	0.70805

7.4.1.2.5 Manufacturing Error: Cadmium is not filtered in Cadmium Chamber

1. The variation of the effective multiplication factor was studied in the extreme cases analysed in previous sections, considering that cadmium, due to an unforeseen error in manufacturing, does not filter into the cadmium chamber.
2. Table 8 shows the cases evaluated, the name of the MCNP input file (as reference), and the effective multiplication factor (k_{eff}) obtained together with its SD, and the final result obtained as k_{eff} plus three times SD.
3. The column identified as "# Cycles" is the total number of KCODE cycles done, each of them issuing two thousand five hundred (2500) fission neutrons.

Table 8: Several cases without cadmium in the cadmium chamber

Case	Reference Name	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
100/250	Ip-Ind_0055.inp	Ip-Ind_0060.inp	2000	0.31989	0.00021	0.32052
1.0	Ip-Ind_0010.inp	Ip-Ind_0061.inp	2000	0.36978	0.00027	0.37059
1000.0	Ip-Ind_0039.inp	Ip-Ind_0062.inp	2000	0.58230	0.00033	0.58329
100/180 – 1.0	Ip-Ind_0815.inp	Ip-Ind_0063.inp	2000	0.70275	0.00035	0.70380

7.4.2 Package array

7.4.2.1 Normal Conditions

1. The multiplication factor for five times "N" packages (384 in this case), without water, is the following:

$$k_{eff} + 3\sigma \quad \sigma < 0.0002 \quad = 0.45798$$

7.4.2.2 Accident Conditions

7.4.2.2.1 Content of Water in Thermal Insulator

1. An analysis took place studying several mixtures of Kaolite 1600 and water. The mass of the thermal insulation was kept constant at a value of 84.4 kg.
2. Table 9 shows the evaluated cases, the name of the MCNP input file (as a reference), the effective multiplication factor (k_{eff}) obtained together with its standard deviation (SD) and the final result as k_{eff} plus three times the SD.

3. The first column shows the relation between the insulating mass and the water considered in the mixture. For example, 100/0 considers the dry insulator, while a value 100/180 indicates a relation 1.8 between the mass of water and the thermal insulator.
4. The column identified as “# Cycles” is the total number of KCODE cycles done, each of them issuing two thousand five hundred (2500) fission neutrons.

Table 9: Multiplication factor for several water mass

Case	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
100/0	lp-0050	1500	0.40055	0.0002	0.40115
100/50	lp-0051	1500	0.28566	0.0002	0.28626
100/100	lp-0052	1500	0.27829	0.0002	0.27889
100/141	lp-0053	1500	0.27834	0.0002	0.27894
100/180	lp-0054	1500	0.27871	0.0002	0.27931
100/250	lp-0055	1500	0.27960	0.0002	0.28020

5. The most unfavourable situation is that of the dry thermal insulator, which is not real since the composite will always retain water after preparation and even after a possible drying.

7.4.2.2.2 Variation of Water Density in Empty Spaces

1. Due to the uncertainty of the way water would enter into packages, several analysis were made in which density of homogenous water was varied, with values which went from 1.0E-7 to 1.0 g/cm^3. Thus, criticality risk can be analysed, associated with the water in the package, as regards the H/U moderation of the package.
2. In a conservative way, the thermal insulator was considered without water.
3. Table 10 shows the evaluated cases, the name of the MCNP input file (as reference), and the effective multiplication factor (k_{eff}) obtained together with its SD, and the final result obtained as k_{eff} plus three times SD.
4. The first column shows density of water in empty spaces. Empty spaces can be seen in Figure 1, indicated as “water or air”.
5. The column identified as “# Cycles” is the total number of KCODE cycles done, each of them issuing two thousand five hundred (2500) fission neutrons.
6. It can be seen that the multiplication factor does not change significantly with the adding of water in empty spaces.

Table 10: Multiplication factor for several water densities

Density	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
1.E-07	lp-0001	2000	0.40251	0.0002	0.40311
1.E-05	lp-0002	1500	0.39586	0.0002	0.39649
1.E-03	lp-0003	1500	0.39604	0.0002	0.39670
1.E-02	lp-0004	1500	0.39780	0.0002	0.39846
0.1	lp-0005	1500	0.36919	0.0002	0.36985
0.2	lp-0006	1500	0.35335	0.0002	0.35401
0.4	lp-0007	1500	0.35630	0.0002	0.35699

0.6	Ip-0008	1500	0.37306	0.0003	0.37381
0.8	Ip-0009	1500	0.39363	0.0003	0.39441
1.0	Ip-0010	1500	0.41528	0.0003	0.41612

7.4.2.2.3 Variation of the Water Mass introduced in Inner Cans

1. The variation of the effective multiplication factor with the adding of different water mass inside the inner cans was studied.
2. The mixture of water and uranium metal was supposed homogenous inside the inner can.
3. In a conservative way, the thermal insulator was taken without water.
4. Table 11 shows the cases evaluated, the name of the MCNP input file (as reference), and the effective multiplication factor (k_{eff}) obtained together with its SD, and the final result obtained as k_{eff} plus three times SD.
5. The first column shows the water mass mixed with uranium metal.
6. The column identified as "# Cycles" is the total number of KCODE cycles done, each of them issuing two thousand five hundred (2500) fission neutrons.
7. C It can be seen that the multiplication factor grows monotonously with the additional water mass added to the uranium metal, and the worst case is a water mass of 1000 g. Due to volume the uranium metal takes in the inner can, not more than 900 g of water can be added.

Table 11: Multiplication factor for several water mass mixed with uranium metal

Water Mass [g]	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
100.0	Ip-0030	2000	0.44283	0.0002	0.44343
200.0	Ip-0031	2000	0.48738	0.0002	0.48798
300.0	Ip-0032	2000	0.53067	0.0003	0.53160
400.0	Ip-0033	2000	0.57112	0.0003	0.57205
500.0	Ip-0034	2000	0.61012	0.0003	0.61105
600.0	Ip-0035	2000	0.64669	0.0003	0.64762
700.0	Ip-0036	2000	0.68170	0.0003	0.68263
800.0	Ip-0037	2000	0.71448	0.0003	0.71541
900.0	Ip-0038	2000	0.74619	0.0003	0.74712
1000.0	Ip-0039	2000	0.77632	0.0003	0.77722

7.4.2.2.4 Variation of Water Mass Introduced simultaneously in Several Compartments

1. The effective multiplication factor was studied when added different water mass inside the inner cans and the empty spaces and the water caught in the thermal insulation.
2. In a conservative way, it was considered, in all cases, a mixture of 1000 g of water and uranium metal inside the inner can. The mixture was supposed to be homogenous inside the inner can.
3. Table 12 shows the cases evaluated, the name of the MCNP input file (as reference), and the effective multiplication factor (k_{eff}) obtained together with its SD and the final result obtained as k_{eff} plus three times SD.

4. The first column shows the water mass mixed with thermal insulation, keeping the same names as in Table 9.
5. The second column is the density of water that entered in empty spaces.
6. The column identified as "# Cycles" is the total number of KCODE cycles done, each of them issuing two thousand five hundred (2500) fission neutrons.
7. It can be seen that the worst case is that in which inner cans are flooded with water (1000 g), the thermal insulator is dry (100/0) and the density of water in empty spaces is insignificant.

Table 12: Variation of quantities of water in combined form

Water Mass [g]	Density of water in Empty Spaces	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
100/0	1.E-05	Ip-0511	2000	0.77868	0.0003	0.77958
	1.E-02	Ip-0512	2000	0.77305	0.0003	0.77395
	0.3	Ip-0513	2000	0.69997	0.0004	0.70117
	0.8	Ip-0514	2000	0.71455	0.0004	0.71575
	1.0	Ip-0515	2000	0.72481	0.0004	0.72601
100/50	1.E-05	Ip-0611	2000	0.64305	0.0003	0.64395
	1.E-02	Ip-0612	2000	0.64378	0.0004	0.64498
	0.3	Ip-0613	2000	0.66060	0.0004	0.66180
	0.8	Ip-0614	2000	0.69571	0.0004	0.69691
	1.0	Ip-0615	2000	0.70948	0.0004	0.71068
100/100	1.E-05	Ip-0711	2000	0.63410	0.0003	0.63500
	1.E-02	Ip-0712	2000	0.63569	0.0003	0.63659
	0.3	Ip-0713	2000	0.65609	0.0003	0.65699
	0.8	Ip-0714	2000	0.69406	0.0004	0.69526
	1.0	Ip-0715	2000	0.70738	0.0004	0.70858
100/141 (nominal)	1.E-05	Ip-0411	2000	0.63343	0.0003	0.63433
	1.E-02	Ip-0412	2000	0.63461	0.0003	0.63551
	0.3	Ip-0413	2000	0.65656	0.0003	0.65746
	0.8	Ip-0414	2000	0.69300	0.0004	0.69420
	1.0	Ip-0415	2000	0.70701	0.0004	0.70821
100/180	1.E-05	Ip-0811	2000	0.63379	0.0003	0.63469
	1.E-02	Ip-0812	2000	0.63463	0.0003	0.63553
	0.3	Ip-0813	2000	0.65638	0.0003	0.65728
	0.8	Ip-0814	2000	0.69345	0.0003	0.69435
	1.0	Ip-0815	2000	0.70751	0.0004	0.70871

7.4.2.2.5 Manufacturing Error: Cadmium is not filtered in Cadmium Chamber

1. The variation of the effective multiplication factor was studied in the extreme cases analysed in previous sections, considering that cadmium, due to an unforeseen error in manufacturing, does not filter into the cadmium chamber.
2. Table 13 shows the cases evaluated, the name of the MCNP input file (as reference), and the effective multiplication factor (k_{eff}) obtained together with its SD, and the final result obtained as k_{eff} plus three times SD.
3. The column identified as "# Cycles" is the total number of KCODE cycles done, each of them issuing two thousand five hundred (2500) fission neutrons.
4. It can be seen that the worst case is again that in which the inner cans are flooded with water (1000 g), the thermal insulator is dry (100/0) and the density of water in the empty spaces is insignificant. This case, for which the highest effective multiplication factor was obtained, shows sub-criticality is assured by large.

Table 13: Several cases without cadmium in the cadmium chamber

Case	Reference Name	Name	# Cycles	k_{eff}	SD	k_{eff}+3SD
100/0	Ip-0050	Ip-0060	2000	0.44659	0.0003	0.44749
1.0	Ip-0010	Ip-0061	2000	0.41667	0.0003	0.41757
1000.0	Ip-0039	Ip-0062	2000	0.81006	0.0004	0.81126
100/0 - 1E-5	Ip-0511	Ip-0063	2000	0.81428	0.0004	0.81548

8 CLASSIFICATION OF LEUPA PACKAGE FOR TRANSPORT BY AIR

8.1 Requirements in accordance with the Standard

1. According with paragraph **680** of the Standard, the packages for transport by air must fulfil the following requirements (a) and (b):

   680. *For packages to be transported by air:*

   a. *The package shall be subcritical under conditions consistent with the Type C package tests specified in para. 734, assuming reflection by at least 20 cm of water but no water in-leakage; and*
   b. *In the assessment of para. 679, allowance shall not be made for special features of para. 677 unless, following the Type C package tests specified in para. 734 and, subsequently, the water in-leakage test of para. 733, leakage of water into or out of the void spaces is prevented.*

8.1.1 Compliance with Paragraph 680 a) and b)

8.1.1.1 Considered Setting

1. To demonstrate compliance with paragraph 680 a), the following setting is supposed:
   a. Once tests required by Standard are finished, the package is completely damaged.
   b. The four inner cans are out of the cadmium chamber. The 50 kg of uranium metal spill and form a homogenous sphere.
   c. The absorbent material (cadmium, steel) is not taken into account, neither moderation of the thermal insulation or hydrogenated material (polyethylene bags).
   d. The homogenous sphere is placed in direct contact with 30 cm of water (higher than the minimum 20 cm established in Standard) with 1.0 g/cm^3 density.

8.1.1.2 Results

1. The multiplication factor for the above setting is the following:

$$\boxed{k_{eff} + 3\sigma \quad \sigma < 0.0004 \quad = 0.69758}$$

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2. This value is lower than the Upper Subcritical Limit (0.9350) established on Reference [5].
3. Suppositions considered in the model are very conservative. It is highly unlikely that the 50 kg of uranium metal, which are normally in four steel inner cans, may spill and make a sphere, and all this without considering the cadmium chamber that contains a great quantity of absorbent.
4. This being considered, and in accordance with the evaluations performed, the package shows compliance with paragraph 680 a) of the Standard.

9 CONCLUSIONS

1. This document demonstrated that the LEUPA package complies with Argentine regulations for the safe transport of 50 kg of uranium metal, by land, by sea and by air, as regards sub-criticality assurance.

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2. All the reported values for the effective multiplication factor (k_{eff}) are lower than the Upper Subcritical Limit (0.9350) established on Reference [5].
3. Since the number of packages considered in the analysis was N = 72, the Criticality Safety Index (CSI) is:

$$\boxed{\mathbf{CSI} = 0.69}$$