LEUPA

Type B(U) Package for Fissile Materials

INDEPENDENT REVIEW OF DOCUMENT 0908-LE01-3BEIN-024-B: LEUPA – CRITICALITY ANALYSIS

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A	Original	MW NG	JLA	JCO	

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1 PURPOSE

1. To prepare an independent review of document 0908-LE01-3BEIN-024-B: LEUPA – Criticality Analysis.

2 SCOPE

1. This document contains a review and expansion of the calculations and conclusions of the criticality analysis for the LEUPA package documented in [2]. This independent review contributes to prove compliance by the LEUPA package with national regulations on safe land, sea or air transport of the fissile substances stated in section 5.1 of the reviewed document, [2], only from the subcriticality assurance standpoint.
2. In this review it is assumed that the N number of packages used in [2] to determine that the Criticality Safety Index (CSI) is the maximum possible. This number was not reviewed other than for the purposes of assuring that the package is safe from the criticality standpoint if N remains as stated in the document reviewed.

3 APPLICABLE STANDARDS AND REFERENCES

[1] Standard AR 10.16.1, "Transport of Radioactive Materials", Revision 2, approved by Resolution of the Board of Directors of the Nuclear Regulatory Authority (ARN) No. 43/11 (Official Gazette 05/11/11). Matches the 2009 Edition of the "Rules for Safe Transport of Radioactive Materials", Group of Safety Standards No. TS-R-1 issued by the International Body of Atomic Energy.

[2] 0908-LE01-3BEIN-024-B: LEUPA – Criticality Analysis. May 30, 2012.

[3] 0908-LE01-3AEIN-004-B: Low Enriched Uranium Package (LEUPA) – General Joint Package.

[4] SCALE, A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation, ORNL/TM-2005/39, Version 6, Vols. I–III, Oak Ridge National Laboratory, Oak Ridge, Tennessee, January 2009. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-750.

[5] B. T. Rearden, "Verification Methods for the SCALE Code System", *Proc. Verification and Validation for Nuclear Systems Analysis Workshop II*, North Myrtle Beach, SC, May 24-28, 2010.

[6] W. J. Marshall and B. T. Rearden, "Criticality Safety Validation of SCALE 6.1 with ENDF/B-VII.0 Libraries", *Trans. Am. Nucl. Soc.* **106**, 456-460 (2012).

4 ABBREVIATIONS

Abbreviation	Description
CSI	Criticality safety index
k_{ef}	Effective multiplication factor
LEUPA	Low Enriched Uranium Package

5 INTRODUCTION

5.1 Description of the Package

1. Reference documents [2] and [3] were used as a basis for this independent review. The purpose is to verify compliance with the applicable standards [1] for subcriticality assurance-related matters.
2. The description of the LEUPA package and the analysis of the various contingencies analyzed are detailed in reference [2], section 5. Everything described in that section of document [2] is considered valid in this document.
3. This document follows the structure of reference document [2] to allow simple follow-up of the criticality analysis and the comments provided herein. The final section includes the conclusions of this independent review.
4. Figure 1: is an axis section of the LEUPA package. The four internal containers with their fissile load, the cadmium cover and main sizes are shown.

Figure 1: LEUPA package (sizes in mm)

Security-Related Information Figure Withheld Under 10 CFR 2.390.

6 MATERIALS USED IN CRITICALITY ASSESSMENTS

1. Table 2 of the reviewed document [2] contains the composition of the materials used in the calculation. Said compositions were reviewed in this work; it was verified that they have been properly evaluated and therefore identical compositions were used in the independent calculations that are part of this review.

7 RATING OF THE LEUPA PACKAGE FOR THE TRANSPORT OF FISSILE SUBSTANCES

7.1 Subcriticality Assurance

1. Section 7.1 of the reviewed document [2] establishes which are the paragraphs of the applicable regulatory standard (Ref. [1], hereinafter referred to as the Standard) the compliance of which is to be assured.
2. In the same section it is clarified that upon preparation of the criticality analysis of the LEUPA package, the tests specified by the Standard had not been carried out. There is no information on the completion of those tests upon preparation of this review, and therefore the hypotheses assumed in the reviewed document [2] (section 7.1, paragraphs 6 to 11) are still adequate and valid as of the preparation of this review.
3. Table 3 in section 7.1 of the document [2] contains a list of the analysis performed and the barriers identified to prove compliance with the provisions in paragraph 671 of the Standard. That paragraph contains a list of the contingencies to be considered to ensure the safe transport of fissile substances under normal or accidental conditions. Table 3 of the document [2] is included herein as Table 1:. A few items have been included in that table to contribute to consolidate all the cases studied, as will be detailed further in this document.

Table 1: Contingencies and confinement barriers identified to ensure subcriticality (as specified in paragraph 671 of the Standard)

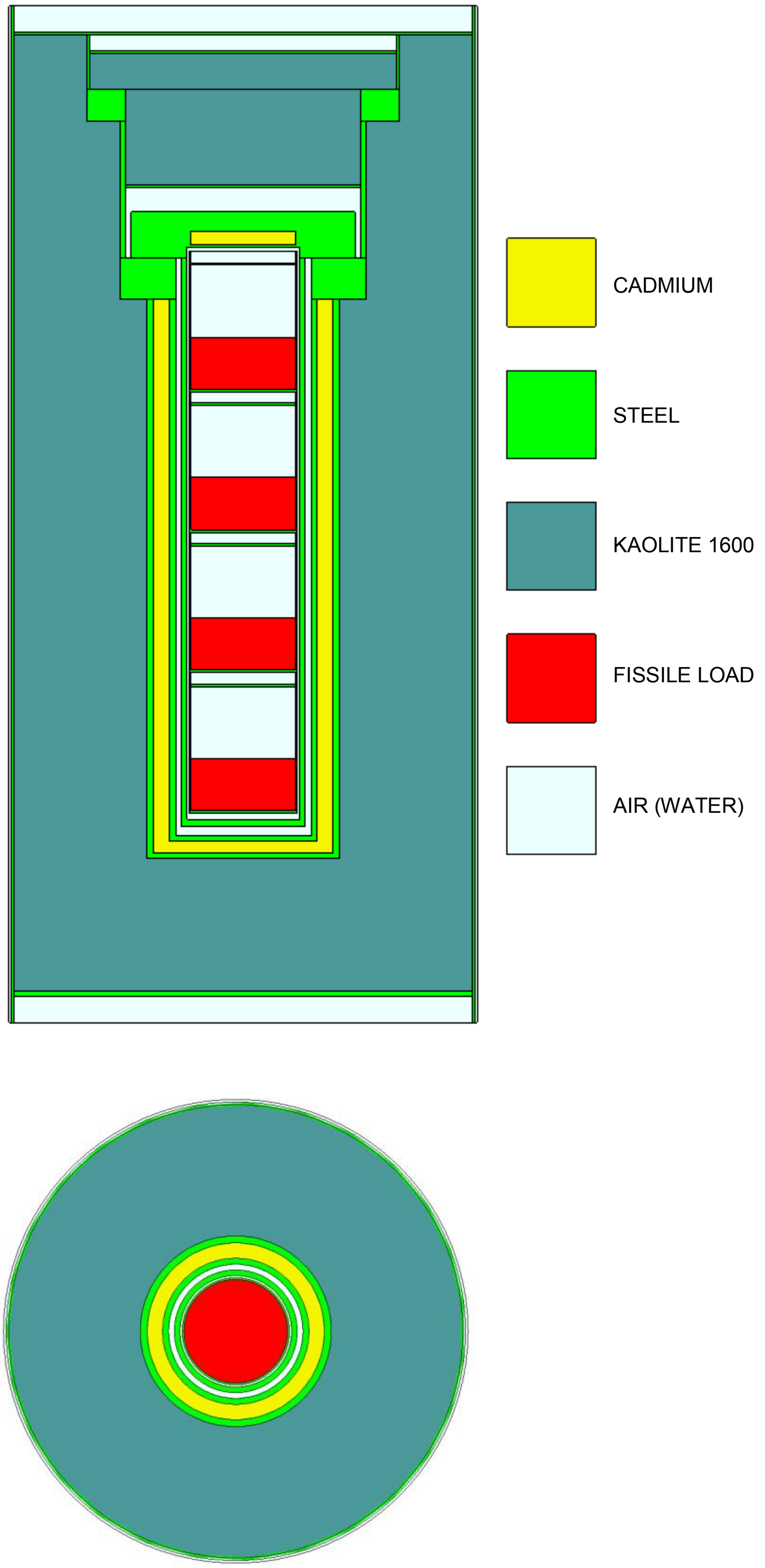
Contingencies	Protection Barriers
(i) Penetration or leakage of water in packages.	Subcriticality of a group of stacked packages (in square or hexagonal disposition) of 6x6x4 packages, with water entering in various configurations.
(ii) Decrease in the efficacy of moderators or neutronic absorbents included in the packages.	Subcriticality of a group of packages displayed in piles (in square or hexagonal disposition) of 6x6x4 packages, even when the absorbent (cadmium) has not been spilled into the cadmium chamber. Subcriticality of the worst-case scenarios analyzed in (i) and (ii) 1.
(iii) Change in the disposition of the content, whether within the package or as a consequence of a leakage of substances.	It is assumed that the integrity of the packaging will remain the same after the tests specified in paragraphs 719 to 724 of the Standard. Subcriticality of the system even with the package inverted in relation to the vertical axis. Subcriticality of a very conservative model described in section 8.
(iv) Decrease of the space within the packages or among them.	It is assumed that the integrity of the packaging will remain the same after the tests specified in Paragraphs 719 to 724 of the Standard.
(v) Immersion of the packages in	Subcriticality of a group of stacked packages (in

Contingencies	Protection Barriers
water or snow.	square or hexagonal disposition) of 6x6x4 packages, with water entering in various configurations.
(vi) Temperature changes.	Subcriticality of a group of packages displayed in piles (in square or hexagonal disposition) of 6x6x4 packages, at room temperature (maximum reactivity).

7.2 Calculation Models and Codes Used

1. Section 7.2 of the reviewed document [2] briefly mentions the calculation code and effective sections used for the calculations included in the document. Both MCNP 4C as the effective sections used are adequate and internationally accepted to calculate the effective multiplication factor of systems with fissile material contents.
2. In this work and for the purposes of obtaining results based on the use of an independent calculation chain, the CSAS6 sequence of the SCALE 6.0 [4] package was used.
3. SCALE is a widely verified and validated calculation system developed to calculate criticality-safety problems, reactor physics, shielding, sensitivity and uncertainties. It has been used for more than 30 years by regulators, licensors and research institutes from all around the world for the analysis of nuclear safety and design [5].
4. Basically, the CSAS6 sequence in SCALE consists on the preparation of effective sequences of the various materials to be used in the calculation, followed by the Monte Carlo calculation with KENO-VI of the modeled system.
5. The calculations which results are included in this work were made using the library of effective sections “v7-238”. This is a multigroup library (238 energy groups) developed based on nuclear data from ENDF/B-VII. The library is conveniently validated for use on criticality calculations for thermal systems containing uranium as fissile material [6].
6. In all the cases calculated with SCALE reported in this document, 1500 active cycles were simulated (10 inactive cycles) with 2500 neutrons per batch.
7. A horizontal section and a vertical section of the LEUPA package are displayed on Figure 2: for the purposes of showing the detail of the geometry modeled in KENO-VI.
8. The most significant measurements of the package (volume of the primary container, thickness of the cadmium absorbent, external measurements of the package) were modeled according to the reference drawing [3]. The geometry of the confinement system cover, intermediate removable cover and external cover was simplified, maintaining the nominal thicknesses and allowing the existence of gaps that can be filled with water when accidental situations are analyzed.
9. Unlike the MCNP model described in reference document [2], in the SCALE model the fissile material does not fill the entire container. Given the real density of uranium metal and the nominal mass transported by each container, only half of the container is full, as we can see in Figure 2:. In [2], a fictitious density was used in order to fill the container while keeping the nominal mass. Both models are, *a priori*, equivalent.

Figure 2: Vertical and horizontal section of LEUPA package in the SCALE model



7.3 Description of the Analyses Performed

1. Section 7.3 of the reviewed document [2] describes the analyses carried out, both under normal and accidental conditions.
2. Following the provisions set forth by the Standard, the "N" number of packages considered for calculation of the CSI is set. It is verified that the selection mode for "N" is appropriate.
3. The hypotheses assumed are correct and meet the requirements in the Standard.
4. The identified accidental conditions adequately cover the potential scenarios. As explained below, in some specific cases other scenarios were added to complete the full set of accident scenarios proposed.

7.4 Results

1. In this section, the results obtained by the independent calculations performed with SCALE are displayed, as well as a comparison with the results reported in the reviewed document [2].

7.4.1 Normal Conditions

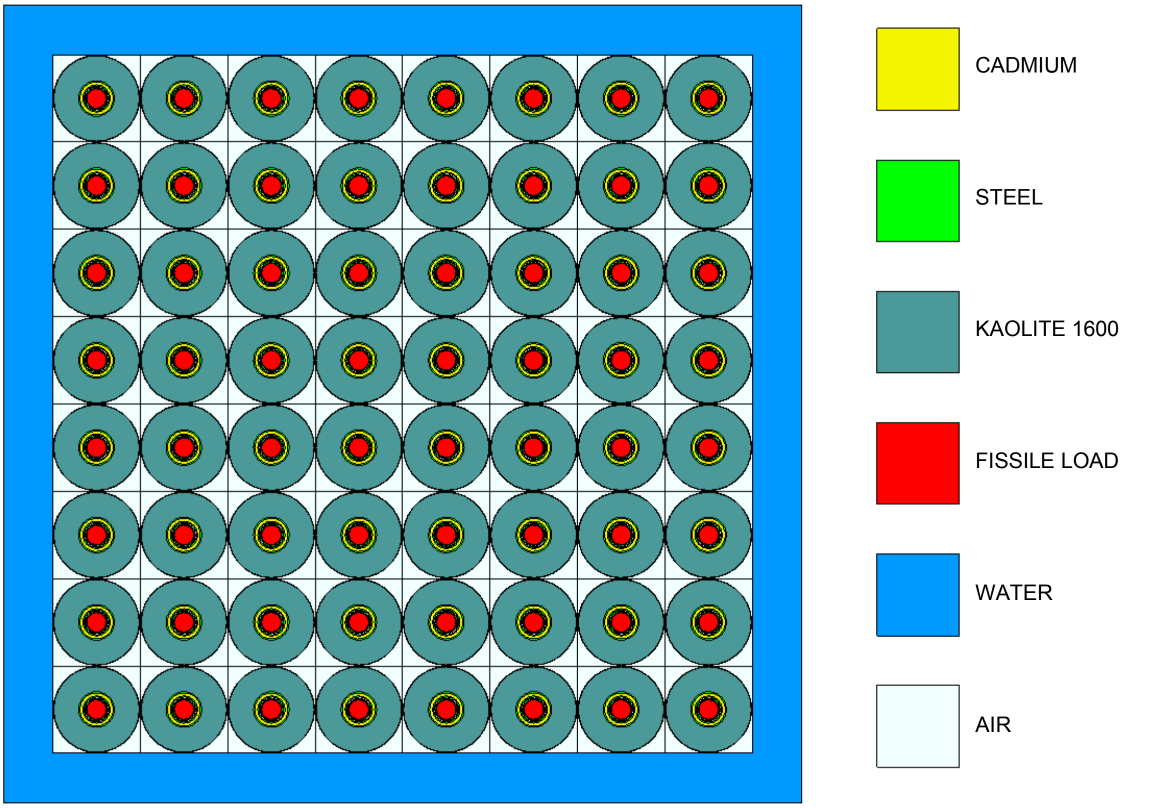
1. The multiplication factor (k_{ef}) for fivefold "N" packages (384 in this specific case), without the presence of water, and with the geometry modeled as described in reference document [2] (MCNP) and section 7.2 (SCALE) is as follows (Figure 3:):

$k_{ef} + 3\sigma$ (σ<0.0003) = 0.53898 (SCALE)
$k_{ef} + 3\sigma$ (σ<0.0002) = 0.45798 (MCNP [2])

2. Although both results indicate that the set of packages is subcritical by a wide margin, there are doubts as regards the reasons for the difference between the results obtained with MCNP and SCALE.
3. In order to understand those differences, two additional calculations were made:
   a. With SCALE, where the fissile material fills the entire interior container (using a fictitious density for uranium in such a way as to fill all the interior container and keeping the nominal mass);
   b. With MCNP, where the fissile material is modeled with its real density, so that the nominal mass fills the interior container only partially, as shown on Figure 2:. This model was developed based on the model used to obtain the results reported in [2].
4. The set of multiplication factors obtained is as follows:

$k_{ef} + 3\sigma$ (σ<0.0003) = 0.53898 (SCALE – U with nominal density)
$k_{ef} + 3\sigma$ (σ<0.0002) = 0.51976 (MCNP – U with nominal density)
$k_{ef} + 3\sigma$ (σ<0.0002) = 0.48040 (SCALE – U with fictitious density)
$k_{ef} + 3\sigma$ (σ<0.0002) = 0.45798 (MCNP – U with fictitious density [2])

Figure 3: Horizontal section of the square arrangement of 5*N LEUPA packages, reflected by 30 cm of water



5. Therefore, differences in the value of k_{ef} calculated by both codes reduced to ~0.02 Δk, considering the differences in the chain of calculation (effective sections and calculation code), and taking into consideration the slight differences in the modeled geometry (empty spaces, detail of intermediate covers), the SCALE calculation confirms what was calculated with MCNP.
6. As an additional result, it is mentioned that maintaining the original density of the fissile material in the container (and therefore modeling the partially filled container when the nominal mass is maintained) results in values higher than the effective multiplication factor of the system, as shown in the results obtained with MCNP and SCALE. This difference should be taken into consideration when comparing the results of MCNP and SCALE that will be presented in the following sections.
7. Given this result, and because the cadmium chamber does not fully cover the container - the cadmium chamber is interrupted in the area of the flange of the container cap, Figure 1: and Figure 2: -, it is also relevant to assess the effect of a potential inversion of the package (i.e., if, for any reason, the package rested on the cover instead of the base). Thus, the fissile load in one of the internal containers would be surrounded by less cadmium than the remaining containers, and it is therefore expected that the reactivity of the system in this situation will be higher. The result of this simulation is as follows:

$k_{ef} + 3\sigma$ ($\sigma<0.0003$) = 0.53898 (SCALE – packages in normal position)
$k_{ef} + 3\sigma$ ($\sigma<0.0003$) = 0.54035 (SCALE – inverted packages)

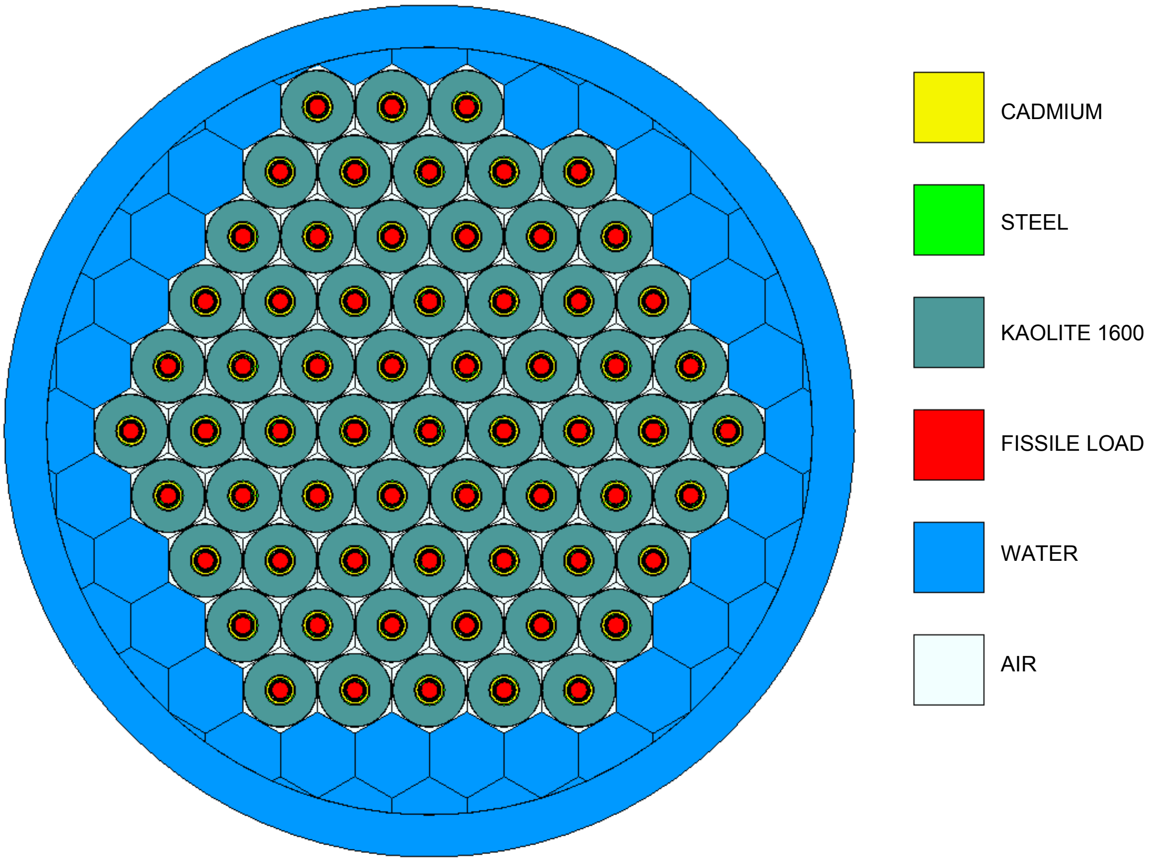
8. The effect of inverting the package is therefore reduced. The modeled case is useful to prove the subcriticality of the packages disposition, regardless of the vertical position of the packages.

9. To evaluate the effect of assuming a different geometric arrangement of packages, a case in which packages are distributed in a hexagonal arrangement was simulated (Figure 4:), keeping the same 6 axial levels assumed on the square disposition. The result is as follows:

$k_{ef} + 3\sigma$ ($\sigma<0.0003$) = 0.53898 (SCALE – square disposition 8x8x6)
$k_{ef} + 3\sigma$ ($\sigma<0.0002$) = 0.56330 (SCALE – hexagonal disposition)

10. The hexagonal arrangement is therefore the most reactive scenario, given that it is the most compact arrangement among the possible regular arrangements. Any other random disposition of packages would be less compact than the hexagonal arrangement proposed, hence its lower reactivity. The modeled case is useful to prove the subcriticality of the system of 5*N packages, regardless of the disposition (vertical or not) of the packages.

Figure 4: Horizontal section of the hexagonal arrangement of 5*N LEUPA packages, reflected by 30 cm (minimum) of water



7.4.2 Accidental Conditions

7.4.2.1 Water Content in the Thermal Insulation

1. The same scenarios described in reference document [2] were simulated with SCALE. This means an analysis to study various mixtures of KAOLITE 1600 and water was conducted. The mass of the thermal insulation was kept constant at 84.4 kg.
2. The results obtained for the evaluated cases are listed in Table 2:. The effective multiplication factor values obtained with MCNP (taken from [2]) and SCALE are included. In the case of MCNP, the values displayed represent k_{ef} plus three times the standard deviation (σ) of the Monte Carlo calculation. In the case of calculations with SCALE, the

most probable value (k_{ef}), the standard deviation of the simulation, and the final result obtained (k_{ef} + 3σ) are displayed. The Δk difference between the results obtained with both codes is listed in the last column.

3. The first column indicates the mass of water retained in the insulation, expressed as a percentage of the total mass of insulation in the package. For instance, 100% implies a retention of 84.4 kg of water in the insulation is modeled (distributed homogeneously throughout the volume of the insulation), while a value of 0% implies dry insulation.

Table 2: Effective multiplication factor (MCNP and SCALE) based on the mass of water retained in the Kaolite 1600

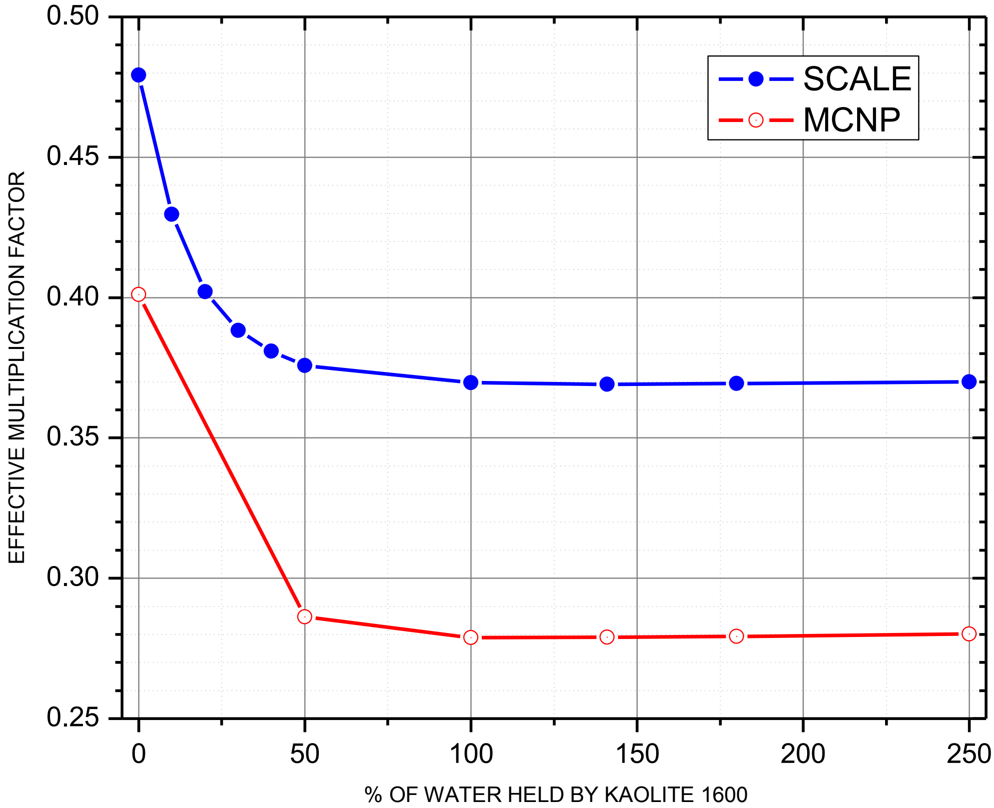
Water Mass [%]	MCNP	SCALE			Δk[(1)]
	k_{ef}+3σ	k_{ef}	σ	k_{ef}+3σ	
0	0.40115	0.47850	0.00025	0.47925	0.078
10		0.42889	0.00024	0.42961	
20		0.40127	0.00025	0.40202	
30		0.38769	0.00021	0.38832	
40		0.38027	0.00021	0.38090	
50	0.28626	0.37512	0.00021	0.37575	0.089
100	0.27889	0.36898	0.00021	0.36961	0.091
141	0.27894	0.36845	0.00023	0.36914	0.090
180	0.27931	0.36872	0.00021	0.36935	0.090
250	0.28020	0.36936	0.00021	0.36999	0.090

(1) (k_{ef}+3σ)(SCALE) – (k_{ef}+3σ)(MCNP)

4. Figure 5: contains a graph on the values of (k_{ef} + 3σ) obtained with MCNP and SCALE, based on the percentage of water retained by the insulation.

5. The SCALE calculation confirms that the most unfavorable situation from the criticality standpoint is the case of dry heat insulation, as stated in [2].

Figure 5: Variation of the effective multiplication factor based on the mass of water retained in the Kaolite 1600



7.4.2.2 Variation of the Density of Water in Empty Spaces

1. In this section, the results obtained in reference document [2], when the inflow of water into the package is analyzed, are verified and expanded. Like in [2], the inflow of water into the existing gaps between internal recipients was simulated with SCALE, between the internal recipients and the cadmium absorbent, around the different caps of the package, and in the spaces between packages. All these regions are indicated as “air (water)” in Figure 2:, and as “air” in 0.
2. As usual in criticality analyses, a parametric study was carried out varying the density of the water infiltrating the listed gaps homogeneously. This way we can analyze the criticality risk associated to the inflow of water into the package based on the related H/U ratio of moderation.
3. The thermal insulation was considered without water content. As mentioned in section 7.4.2.1, paragraph 5, this condition of water content in the insulation is the most unfavorable from the criticality standpoint.
4. Table 3: contains a list of multiplication factor values obtained with MCNP (second column, taken from Table 5 in [2]) and SCALE (third column), when simulating an homogeneous water inflow through all the gaps inside the packages and among packages, based on the density assumed for the water inflow. The Δk difference between the results obtained with both codes is listed in the fourth column.
5. Figure 6: shows the values calculated with MCNP (red curve, empty circles) and SCALE (blue curve, solid circles). The existence of a minimum based on the density of the water entering the package suggests the presence of phenomena competing among them in relation to the reactivity of the system. In order to identify and separate these phenomena, another series of calculations was prepared, where the inflow of water to the package was

simulated, but only to empty spaces located within the confinement system. In other words, we simulate a scenario where there is water inflow only through empty spaces located on the inside of the cadmium cover. The results obtained are shown in the last 3 columns of Table 3:, under the heading "SCALE* (H_2O confinement only)".

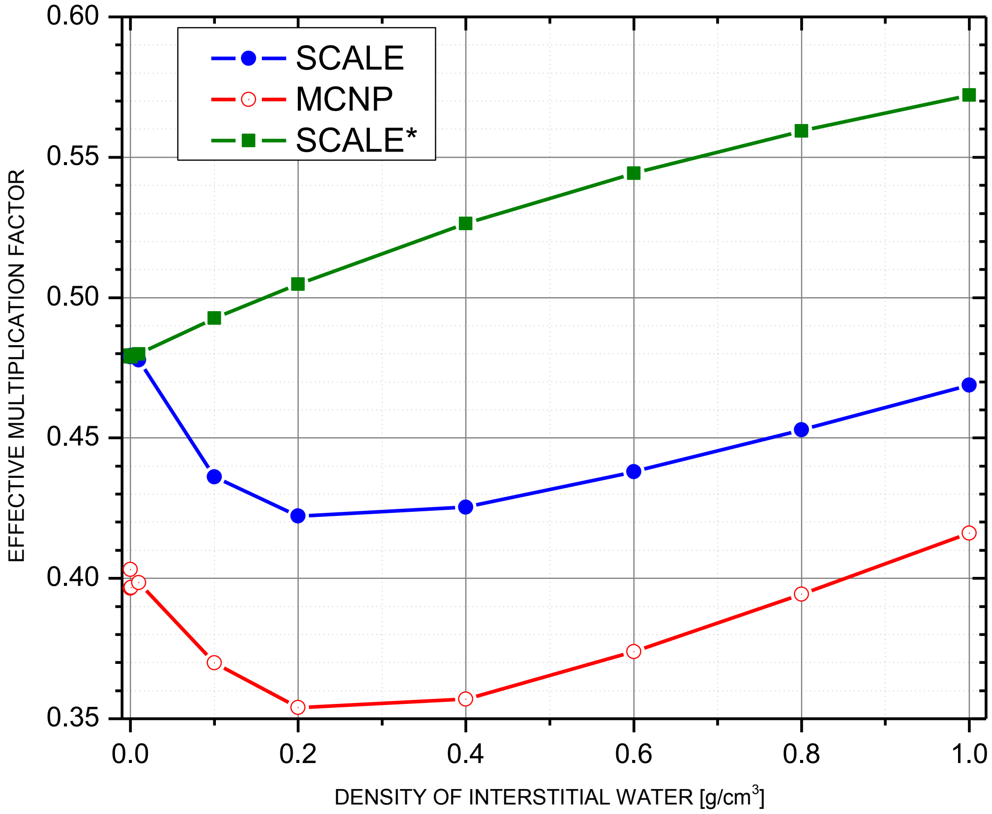
Table 3: Effective multiplication factor for various densities of water entering through empty spaces inside and outside the package

Density [g/cm^3]	MCNP	SCALE	$\Delta k^{(1)}$	SCALE* (H_2O confinement only)		
	$k_{ef}+3\sigma$	$k_{ef}+3\sigma$		k_{ef}	σ	$k_{ef}+3\sigma$
10^{-7}	0.40311	0.47931	0.076	0.47807	0.00027	0.47888
10^{-5}	0.39649	0.47893	0.082	0.47872	0.00027	0.47953
10^{-3}	0.39670	0.47936	0.083	0.47814	0.00025	0.47889
0.01	0.39846	0.47778	0.079	0.47909	0.00025	0.47984
0.1	0.36985	0.43618	0.066	0.49204	0.00024	0.49276
0.2	0.35401	0.42225	0.068	0.50390	0.00030	0.50480
0.4	0.35699	0.42528	0.068	0.52558	0.00026	0.52636
0.6	0.37381	0.43795	0.064	0.54334	0.00030	0.54424
0.8	0.39441	0.45287	0.058	0.55844	0.00029	0.55931
1.0	0.41612	0.46879	0.053	0.57126	0.00031	0.57219

(1) $(k_{ef}+3\sigma)$(SCALE) – $(k_{ef}+3\sigma)$(MCNP)

6. The curve indicated as "SCALE *" (green curve) in Figure 6: shows that the more reactive case is that where the water inflow only to the existing empty spaces inside the cadmium cover is simulated. This water provides moderation to the sub-moderate system and therefore the multiplication factor increases with the inflow of water.
7. On the contrary, when water is also added outside the cadmium cover, the additional moderation obtained does not translate into an increase of the effective multiplication factor of the system, since the thermalized neutrons in the area outside the cadmium cover are absorbed in the cadmium before re-entering the containers with fissile material.

Figure 6: Variation of the effective multiplication factor based on the density of water entering the empty spaces inside and outside the package



7.4.2.3 Variation of the Mass of Water Entering the Inner Containers

1. In this section, the results obtained in reference document [2] when the inflow of water into internal containers with fissile materials are analyzed and verified.
2. The variation of the effective multiplication factor was studied based on the inflow of water inside the internal containers.
3. Just as in [2], the mixture of water and uranium metal was assumed to be homogeneous within the internal container. In [2] (MCNP calculations), the density of the homogeneous mixture of water+uranium metal was calculated so that the proposed mixture of water+uranium filled up all the useful volume of the inner container. As mentioned in section 7.2, paragraph 9, in calculations with SCALE presented in this report, the mixture has a density calculated based on the densities of the individual components, and therefore the height of the mixture in the container varies as the incoming water mass increases.
4. In a conservative manner, in all cases it was considered that the thermal insulation does not contain water.
5. The results are listed in Table 4:. The first column indicates the mass of water entering each internal container. The effective multiplication factor values obtained with MCNP (taken from [2]) and SCALE are included in the following columns. In the case of MCNP, the values displayed represent k_{ef} plus three times the standard deviation (σ) of the Monte Carlo calculation. In the case of calculations with SCALE, the height of the mixture of water+uranium metal in each interior container, the calculated value of k_{ef}, its standard deviation, and the final result obtained ($k_{ef} + 3\sigma$) are indicated. The Δk difference between the results obtained with both codes is listed in the last column.

Table 4: Effective multiplication factor based on the water mass entering each internal container

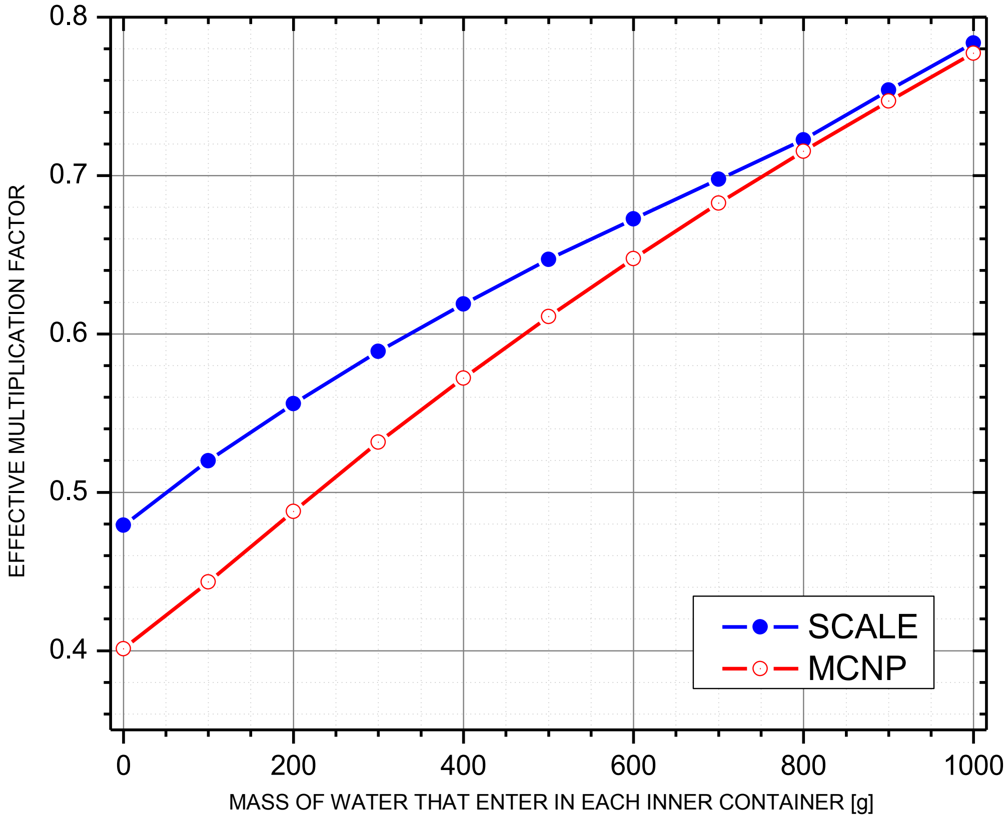
Water [g]	MCNP	SCALE				Δk[(1)]
	$k_{ef}+3\sigma$	Height [cm]	k_{ef}	σ	$k_{ef}+3\sigma$	
0	0.40115	6.92	0.47850	0.00025	0.47925	0.078
100	0.44343	7.82	0.51903	0.00031	0.51996	0.077
200	0.48798	8.72	0.55480	0.00036	0.55588	0.068
300	0.53160	9.62	0.58786	0.00036	0.58894	0.057
400	0.57205	10.52	0.61799	0.00032	0.61895	0.047
500	0.61105	11.42	0.64591	0.00036	0.64699	0.036
600	0.64762	12.32	0.67144	0.00037	0.67255	0.025
700	0.68263	13.22	0.69629	0.00045	0.69764	0.015
800	0.71541	14.1[(2)]	0.72137	0.00036	0.72245	0.007
900	0.74712	14.1[(2)]	0.75280	0.00039	0.75397	0.007
1.000	0.77722	14.1[(2)]	0.78250	0.00040	0.78370	0.006

(1) $(k_{ef}+3\sigma)$(SCALE) – $(k_{ef}+3\sigma)$(MCNP)

(2) full internal container

6. Figure 7: contains the calculated values.
7. We can see that the multiplication factor increases monotonously with the water mass entering the inside container. Be it reminded that, given the measurements of the internal containers and the nominal mass of uranium metal per container, it is not possible to add more than 900 g of water per internal container.
8. In all cases, the value calculated with SCALE is higher than the value calculated with MCNP. The difference between both calculations is reduced to a minimum as the mixture of water+uranium metal modeled in SCALE fills the free volume of each interior container, since the differences in the fissile volume modeled with both codes is reduced when water is added to the container. This behavior confirms what is stated in section 7.4.1, paragraphs 3 to 6.

Figure 7: Variation of the effective multiplication factor based on the mass of water entering each internal container



7.4.2.4 Variation of the Water Mass Introduced Simultaneously into Several Compartments

1. In this section, the results obtained in reference document [2] when the water enters simultaneously into various compartments of the package are analyzed, verified and expanded.
2. We studied the variation of the effective multiplication factor with the addition of different water masses within the thermal insulation, empty spaces and within internal containers. In other words, it is the combination of the cases analyzed in sections 7.4.2.1, 7.4.2.2 and 7.4.2.3.
3. Conservatively (based on the results shown in section 7.4.2.3), a mixture of 1000 g of water and uranium metal within the inner container was considered. The mixture of water and uranium metal was assumed to be homogeneous and occupy the entire volume of the internal container's free volume.
4. In these conditions, and for a certain water mass added to the thermal insulator (expressed as a percentage of the nominal mass of insulation per package), the inflow of water to the empty gaps inside the package and between packages was simulated. The water entering these gaps was simulated with different densities, so as to cover the entire universe of potential moisture/flood scenarios.
5. Table 5: shows all the results obtained.
6. The first column indicates the water mass mixed with the thermal insulation, expressed as a percentage of the nominal mass of thermal insulation (84.4 kg per package).
7. The second column is the density of the water that entered the empty spaces.

8. The effective multiplication factor values obtained with MCNP (taken from [2]) and SCALE are listed in the following column. In the case of MCNP, the values displayed represent k_{ef} plus three times the standard deviation (σ) of the Monte Carlo calculation. In the case of calculations with SCALE, the calculated value of k_{ef}, its standard deviation, and the final result obtained (k_{ef} + 3σ) are displayed.
9. The Δk difference between the results obtained with both codes is listed in the last column.
10. Based on the results described in section 7.4.2.2, paragraph 6, another subset of cases simulating the inflow of water only to empty spaces inside the confinement system of packages (i.e., to the inside of the cadmium cover), when the thermal insulation is simulated dry, are added to the cases simulated cases in [2].
11. It is precisely in this group of cases calculated with SCALE where the more reactive case is identified: internal containers flooded with water (1000 g water per container), dry thermal insulation, and maximum density of water in empty spaces located inside the confinement.
12. Cases resulting in the maximum k_{ef} obtained with MCNP and SCALE are highlighted in Table 5:.
13. Figure 8: contains a graph of the results obtained with MCNP and SCALE, for cases where the insulation is dry, for different densities of water entering the gaps (homogeneous inflow of water in all the gaps of packages, and inflow of water only to the gaps located to the interior of the confinement, indicated with the label "SCALE *" in Figure 8:).
14. In all those cases, a square arrangement of packages was simulated in the system. Figure 8: also shows a calculation point that corresponds to the simulation of a hexagonal arrangement of packages in the system (k_{ef} + 3σ = 0.84234).

Table 5: Effective multiplication factor for different amounts of water retained in the Kaolite 1600 based on the density of water inside the gaps of packages

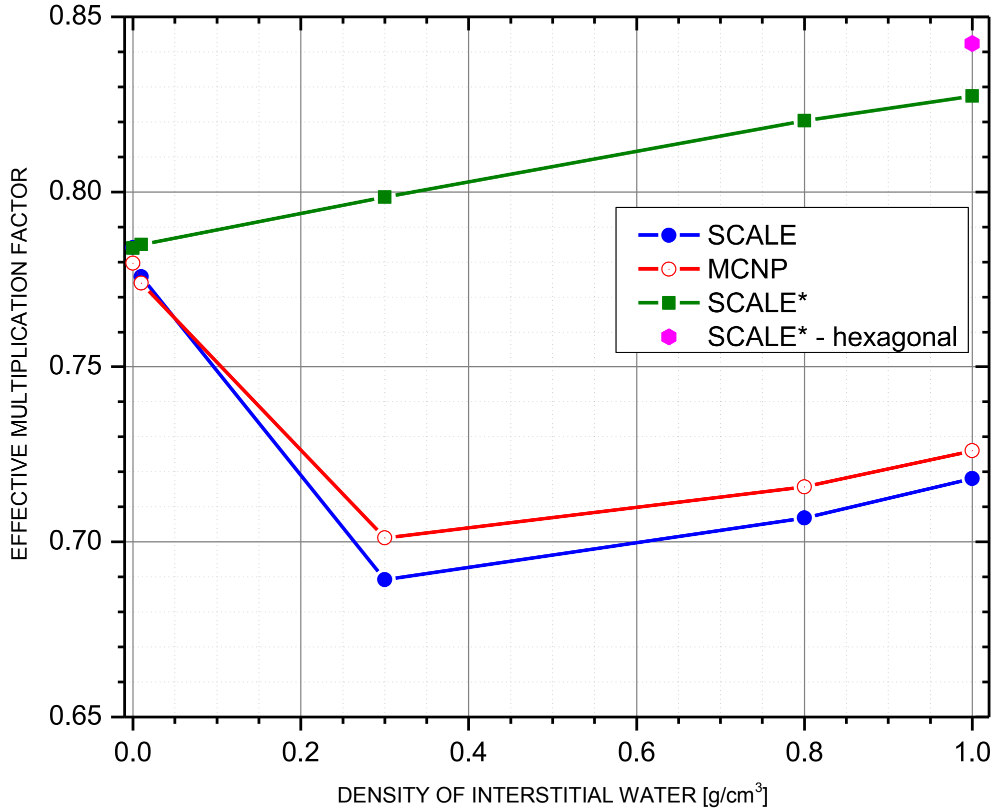
Water Mass [%]	Water Density [g/cm^3]	MCNP k_{ef}+3σ	SCALE			Δk(1)
			k_{ef}	σ	k_{ef}+3σ	
0	10^{-5}	0.77958	0.78284	0.00040	0.78404	0.004
	0.01	0.77395	0.77460	0.00040	0.77580	0.002
	0.3	0.70117	0.68810	0.00036	0.68918	-0.012
	0.8	0.71575	0.70571	0.00038	0.70685	-0.009
	1.0	0.72601	0.71680	0.00043	0.71809	-0.008
0 (with water inflow only to the interior of the confinement)	10^{-5}		0.78254	0.00046	0.78392	
	0.01		0.78376	0.00040	0.78496	
	0.3		0.79729	0.00039	0.79846	
	0.8		0.81913	0.00040	0.82033	
	1.0		0.82602	0.00045	0.82737	
	1.0(2)		0.84108	0.00042	0.84234	

Water Mass [%]	**Water Density [g/cm^3]**	**MCNP $k_{ef}+3\sigma$**	**SCALE**			**Δk(1)**
			k_{ef}	**σ**	**$k_{ef}+3\sigma$**	
50	10^{-5}	0.64395	0.63997	0.00038	0.64111	-0.003
	0.01	0.64498	0.63992	0.00043	0.64121	-0.004
	0.3	0.66180	0.65558	0.00041	0.65681	-0.005
	0.8	0.69691	0.69174	0.00042	0.69300	-0.004
	1.0	0.71068	0.70571	0.00039	0.70688	-0.004
100	10^{-5}	0.63500	0.62993	0.00036	0.63101	-0.004
	0.01	0.63659	0.63014	0.00037	0.63125	-0.005
	0.3	0.65699	0.65073	0.00037	0.65184	-0.005
	0.8	0.69526	0.68897	0.00043	0.69026	-0.005
	1.0	0.70858	0.70450	0.00039	0.70567	-0.003
141	10^{-5}	0.63433	0.62847	0.00038	0.62961	-0.005
	0.01	0.63551	0.62901	0.00038	0.63015	-0.005
	0.3	0.65746	0.65120	0.00039	0.65237	-0.005
	0.8	0.69420	0.68959	0.00039	0.69076	-0.003
	1.0	0.70821	0.70477	0.00041	0.70600	-0.002
180	10^{-5}	0.63469	0.62871	0.00038	0.62985	-0.005
	0.01	0.63553	0.62859	0.00037	0.62970	-0.006
	0.3	0.65728	0.65039	0.00039	0.65156	-0.006
	0.8	0.69435	0.68988	0.00039	0.69105	-0.003
	1.0	0.70871	0.70505	0.00039	0.70622	-0.002

(1) $(k_{ef}+3\sigma)$(SCALE) – $(k_{ef}+3\sigma)$(MCNP)

(2) hexagonal arrangement of packages

Figure 8: Variation of the effective multiplication factor depending on the density of water entering the gaps in the packages arrangement, when the insulation is dry



7.4.2.5 Manufacturing Error: Cadmium does not Infiltrate Into the Cadmium Chamber

1. This section contains an analysis, verification and expansion of the results reported in section 7.4.2.5 of reference document [2].
2. The effect of an unnoticed manufacturing error preventing cadmium from infiltrating to the cadmium chamber, on the effective multiplication factor of the 6 x 6 x 4 arrangement of packages was analyzed. This condition was analyzed for extreme cases reported in section 7.4.2.5 of [2], and also for additional cases described in the following paragraphs.
3. In all cases it is considered that there is no absorbent material in the cadmium chamber, and that the thermal insulation contains no water (dry thermal insulator).
4. In the cases reported in [2] and equivalent cases calculated with SCALE, the cadmium chamber remains empty. In another group of cases calculated with SCALE, the chamber is filled with water with different densities, in order to assess the impact of the addition of moderator on the reactivity of the system.
5. The results are listed in Table 6:. The first column indicates the way in which the inflow of water to the package was simulated. The second column indicates the water mass entering each internal vessel, while the third column is the density of the water entering the empty spaces.
6. The first group of results contains the results obtained with MCNP, reported in [2]. Next, the results obtained with SCALE, reported as in the previous sections. The maximum value of k_{ef} obtained with MCNP is highlighted with a box. The same case, calculated with SCALE, results in a very similar value.
7. Due to the effect shown in the section 7.4.2.2, paragraphs 5 and the following paragraphs, several cases were analyzed in addition to those reported in [2]. The idea behind these

cases is to separate the moderation effect from the absorption effect added by the added water, depending on the region in the system in which the water is added.

8. Thus, three groups of additional cases were calculated:
   a. With inflow of water to all the empty spaces within the package and among the packages, marked with the tag “homogeneous” in Table 6: and Figure 9:.
   b. With inflow of water only to the empty spaces within the confinement system, marked with the tag “confinement” in Table 6: and Figure 9:.
   c. With inflow of water only to the empty spaces within the confinement system and also the empty space in the cadmium chamber, marked with the tag “confinement and Cd chamber” in Table 6: and Figure 9:.
9. The curve displayed in Figure 8: is repeated in Figure 9: when water enters only the interior of the confinement (curve labeled as “confinement - with Cd”), for the sole purpose of making the effect of removing the cadmium from the cadmium cover visible.
10. In all those cases, a square arrangement of packages was simulated in the system. Figure 9: also shows a calculation point that corresponds to the simulation of a hexagonal arrangement of packages in the system ($k_{ef} + 3\sigma = 0.87083$).
11. It can be seen that, again, the worst case is the one in which internal containers are flooded with water (1000 g of water), the insulation is dry, water enters only into the gaps within the confinement, and the density of water in these empty spaces is equal to 1 g/cm^3. This case, which yielded the highest effective multiplication factor of all those evaluated so far, shows that even under the hypothesis of this accidental case, the subcriticality of the packages system is assured with one sufficient margin.

Table 6: Effective multiplication factor for several cases without cadmium in the cadmium chamber

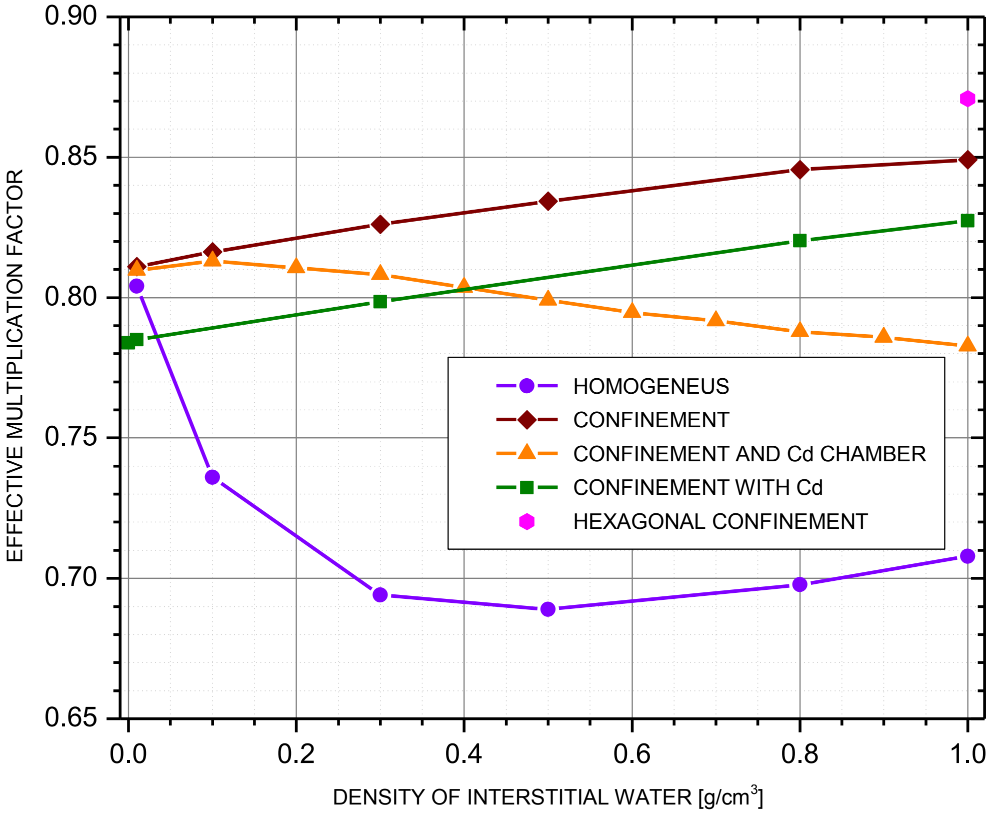
Water Inflow	Water [g]	Water Density [g/cm^3]	MCNP	SCALE			$\Delta k^{(1)}$
			$k_{ef}+3\sigma$	k_{ef}	σ	$k_{ef}+3\sigma$	
	0	0	0.44749	0.50494	0.00027	0.50575	0.058
	0	10^{-3}	0.41757	0.50575	0.00026	0.50653	0.089
	1.000	0	0.81126	0.80947	0.0004	0.81067	-0.001
	1.000	10^{-5}	0.81548	0.80904	0.00042	0.81030	-0.005
	0	1		0.59569	0.00039	0.59686	
Homogeneous	1.000	0.01		0.80289	0.00040	0.80409	
	1.000	0.1		0.73473	0.00044	0.73605	
	1.000	0.3		0.69291	0.00040	0.69411	
	1.000	0.5		0.68762	0.00042	0.68888	
	1.000	0.8		0.69646	0.00041	0.69769	
	1.000	1		0.70668	0.00039	0.70785	
Confinement	1.000	0.01		0.80985	0.00041	0.81108	
	1.000	0.1		0.81487	0.00045	0.81622	
	1.000	0.3		0.82482	0.00042	0.82608	
	1.000	0.5		0.83304	0.00042	0.83430	
	1.000	0.8		0.84431	0.00041	0.84554	

Water Inflow	Water [g]	Water Density [g/cm^3]	MCNP	SCALE			Δk(1)
			$k_{ef}+3\sigma$	k_{ef}	σ	$k_{ef}+3\sigma$	
	1.000	1		0.84778	0.00046	0.84916	
	1.000	1(2)		0.86963	0.00040	0.87083	
Confinement and Cd Chamber	1.000	0.01		0.80849	0.00042	0.80975	
	1.000	0.1		0.81166	0.00043	0.81295	
	1.000	0.2		0.80929	0.00043	0.81058	
	1.000	0.3		0.80672	0.00047	0.80813	
	1.000	0.4		0.80249	0.00039	0.80366	
	1.000	0.5		0.79785	0.00041	0.79908	
	1.000	0.6		0.79346	0.00039	0.79463	
	1.000	0.7		0.79001	0.00057	0.79172	
	1.000	0.8		0.78660	0.00042	0.78786	
	1.000	0.9		0.78453	0.00043	0.78582	
	1.000	1		0.78148	0.00041	0.78271	

(1) $(k_{ef}+3\sigma)$(SCALE) – $(k_{ef}+3\sigma)$(MCNP)

(2) hexagonal arrangement of packages

Figure 9: Multiplication factor depending on the density of the interstitial water, for different cases in which cadmium did not infiltrate into the cadmium chamber



8 RATING OF THE LEUPA PACKAGE FOR AIR TRANSPORTATION

1. This section contains a review of the hypotheses considered, and an analysis and verification of the results reported in section 8 of reference document [2].
2. The requirements to be met pursuant to the Standard are indicated in section 8.1 of reference document [2].
3. The scenario posed to verify compliance with the requirements of the Standard implies complete destruction of the packaging, with a spill of 50 kg of the uranium metal transported. This uranium forms a homogeneous sphere which is reflected with 30 cm of water. Credit is not given to the absorbent material (cadmium and steel), nor the moderation of the thermal insulator.
4. In reference document [2] there is also no credit given to the additional moderation that could be provided by the polyethylene packaging. In this work, this effect is assessed by reproducing not only the same case as that stated in the reference document, but also adding the case in which the polyethylene packaging is homogeneously mixed with uranium metal.

8.1 Results

1. The multiplication factor obtained for each of the two analyzed scenarios are shown below, together with the result taken from [2]:

$k_{ef} + 3\sigma$ ($\sigma<0.0004$) = 0.69758 (MCNP - [2])
$k_{ef} + 3\sigma$ ($\sigma<0.0003$) = 0.69875 (SCALE – same hypothesis as in [2])
$k_{ef} + 3\sigma$ ($\sigma<0.0004$) = 0.73727 (SCALE – polyethylene and uranium metal)

2. It is confirmed that even under the conservative conditions assumed (including the moderation provided by polyethylene packaging), the system is subcritical by a wide margin.
3. Thus, it is confirmed that the package complies with the requirements of the Standard for air transportation.

9 CONCLUSIONS

1. A full and independent review of reference document [2] was carried out. The independence claimed refers both to the analyst in charge of the review and the calculation tools used (effective section libraries) and calculation code).
2. As a result of this independent review, we can state the following:
   a. The scenarios proposed in the reference document to prove compliance with the Standard are adequate, but not exhaustive.
   b. There are more reactive scenarios than those proposed in the reference document, which have been identified and calculated in this independent review.
   c. The results presented in this work using a different calculation system are consistent with the results reported in reference document [2].
   d. The results obtained by the simulation of the scenarios proposed in [2] together with those scenarios added in this independent review, confirm that in all cases the system remains subcritical by a sufficient subcriticality margin, thus complying with the requirements of the Standard.
3. Under normal conditions, the effect of assuming a hexagonal geometric arrangement of packages was evaluated, in addition to the square arrangement proposed in the reference document. The hexagonal arrangement is more reactive, but even under these conditions the system is subcritical by a wide margin.
4. In addition to the accidental scenarios proposed in the reference document, this review has identified one specific scenario which turned out to be more reactive than those proposed in [2]. However, even in that scenario, and even when the disposition of packages is assumed to be hexagonal, the system remains subcritical by a sufficient margin.
5. In this document it was assumed that the N number of packages used to determine the CSI is the maximum number of packages possible. In all the scenarios analyzed to ensure that the package is safe from the criticality point of view, the N number has remained the same as in the scenarios presented in reference document [2].
6. Therefore, the reference document and its independent review presented herein have shown that the LEUPA package meets the requirements set forth by Argentine regulations for the safe transport of 50 kg of uranium metal by land, sea and air, from a subcriticality assurance standpoint.
7. Because the number of packages considered in the analysis was N = 72, the Criticality Safety Index (CSI) is:

CSI = 0.69

10 LIST OF SCALE ENTRY FILES

File name	Comments
leupa_8x8x6	Square arrangement 8x8x6 (5xN) packages without the presence of water in gaps, reflected by 30 cm of water, with fissile load with its nominal density (section 7.4.1).
leupa_8x8x6_filled	The same as the prior item, but with fissile load with fictitious density in order to completely fill the internal containers (section 7.4.1).
leupa_8x8x6_alreves	Fissile load with nominal density, inverted packages (section 7.4.1).
leupa_8x8x6_shexagonal	Hexagonal arrangement of 5xN packages (section 7.4.1).
l664_akXXX_ch2	Square arrangement of 6x6x4 (2xN) packages, reflected by 30 cm of water, Kaolite with water content equal to XXX% of the Kaolite mass, without inflow of water into the gaps (Table 2:).
l664_dXX_ch2	Square arrangement of 6x6x4 (2xN) packages, reflected by 30 cm of water, Kaolite without water content, with homogeneous inflow of water with density XX in all the gaps of the package outside the interior container, and in the gaps between packages (Table 3:).
l664_h2oin_dXX_ch2	Square arrangement of 6x6x4 (2xN) packages, reflected by 30 cm of water, Kaolite without water content, with homogeneous inflow of water with density XX only in the gaps of the package to the interior of the confinement, and outside the internal container (Table 3:).
l664_aXXXX_ch2	Square arrangement of 6x6x4 (2xN) packages, reflected by 30 cm of water, Kaolite without water content, without water in the gaps, with inflow of XXXX grams of water to the inside of each interior container (Table 4:).
l664_a1000_akXXX_dYY_ch2	Square arrangement of 6x6x4 (2xN)

File name	Comments
	packages, reflected by 30 cm of water, with inflow of 1000 grams of water to the inside of each internal container, Kaolite without water content equal to XXX% of the Kaolite mass, with homogeneous inflow of water with density YY in all the gaps of the package outside the inner container, and in the gaps between packages (Table 5:).
l664_a1000_ak000_h2oin_dYY_ch2	Square arrangement of 6x6x4 (2xN) packages, reflected by 30 cm of water, with inflow of 1000 grams of water to the inside of each internal container, Kaolite without water content, with homogeneous inflow of water with density YY only in the gaps of the package to the interior of the confinement (Table 5:).
l664_nocd_a1000_ak000_dYY_ch2	Square arrangement of 6x6x4 (2xN) packages, reflected by 30 cm of water, with inflow of 1000 grams of water to the inside of each internal container, Kaolite without water content, with homogeneous inflow of water with density YY in all the gaps of the package outside the interior container, and in the gaps between packages, with the cadmium chamber with no cadmium and empty (Table 6:).
l664_nocd_a1000_ak000_h2oin_dYY_ch2	Square arrangement of 6x6x4 (2xN) packages, reflected by 30 cm of water, with inflow of 1000 grams of water to the inside of each internal container, Kaolite without water content, with homogeneous inflow of water with density YY only in the gaps inside the package to the interior of the confinement, with the cadmium chamber with no cadmium and empty (Table 6:).
l664_nocdh2o_a1000_ak000_h2oin_dYY_ch2	Square arrangement of 6x6x4 (2xN) packages, reflected by 30 cm of water, with inflow of 1000 grams of water to the inside of each internal container, Kaolite without water content, with homogeneous inflow of water with density YY only in the gaps of the package to the interior of the confinement, and the interior of the cadmium chamber (Table 6:).
leupa_esfera_ch2	50 kg of uranium metal and 100 g of

File name	Comments
	polyethylene, forming a homogeneous sphere, reflected by 30 cm of water.