RAPPORT

IRSN
INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Faire avancer la sûreté nucléaire

Design of experiments involving molybdenum in SNL SPRF/CX facility

IER 305 - CED 2 report

N. LECLAIRE

Rapport n°IRSN/2020-000464

Pôle sûreté des installations et des systèmes nucléaires
Recherche en sûreté

Service de neutronique et des risques de criticité
Laboratoire de neutronique
Bâtiment n°25, FAR, 92262, Fontenay-Aux-Roses

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Nom/*Name*	N. LECLAIRE	I. DUHAMEL J. TAFOREAU	S. PIGNET	O. MARCHAND	P. GIORDANO p.o. T. ALBIOL
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RÉSUMÉ

Mots clés : Expérience critique, Dimensionnement, Molybdène, Optimisation, Sandia

Ce rapport s'inscrit dans le cadre de la collaboration avec le Nuclear Criticality Safety Program et constitue le « CED-2 report » des expériences proposées par l'IRSN dans l'installation SPRF/CX de SANDIA National Laboratories pour contribuer à la qualification du Molybdène en spectre thermique. Il complète l'étude réalisée dans le rapport CED-1 en fournissant une définition plus précise des expériences proposées et présente une évaluation complète des incertitudes expérimentales. Dans le rapport CED-1, correspondant au design préliminaire des expériences, l'IRSN a identifié plusieurs configurations prometteuses qui pourraient être mises en œuvre dans l'installation SPRF/CX de SNL. Celles-ci mettent en œuvre le molybdène métallique soit sous forme de feuillets entre les pastilles UO_2 à l'intérieur de crayons BUCCX, soit sous forme de surgaines entourant des crayons 7uPCX.

Dans ce rapport CED-2, un nouveau design mettant en œuvre le molybdène sous forme de surgaines entourant des crayons BUCCX a également été analysé et les incertitudes expérimentales de toutes les configurations proposées ont été estimées. Compte tenu des contraintes au niveau de la réalisation des expériences et des coûts associés à la fabrication des feuillets, les expériences mettant en œuvre des feuillets de molybdène ont été écartées. De façon similaire, le design mettant en œuvre des surgaines de molybdène autour des crayons BUCCX présente des coûts de fabrication importants qui pourraient être certes en partie compensés par l'économie de la fabrication de grilles de maintien (utilisation de grilles existantes) mais qui conduirait à des valeurs des sensibilités intégrales aux sections du molybdène légèrement plus faibles. En conséquence, le design mettant en œuvre des surgaines de molybdène autour des crayons 7uPCX doit être privilégié dans la mesure où il présente les sensibilités du k_{eff} aux sections du molybdène les plus importantes et qu'il existe une marge en termes de réduction du nombre de crayons avec surgaines permettant de réduire le coût des expériences. Du point de vue du retour d'expérience sur les données nucléaires en support à l'expertise, l'un des avantages des travaux décrits ici est que les expériences proposées ne sont pas corrélées aux expériences MIRTE et PF mettant en œuvre du molybdène. De plus, elles conduisent à des valeurs de sensibilité plus élevées dans la gamme d'énergie thermique que les expériences existantes et « couvrent » en partie la première résonance du ^{95}Mo, ce qui présente un réel avantage pour avoir une meilleure connaissance des sections efficaces du molybdène.

ABSTRACT

Key-words: Design, Molybdenum, Optimization, Sandia

This report is part of the collaboration with the Nuclear Criticality Safety Program and constitutes the "CED-2 report" of the experiments proposed in the SPRF/CX facility of SANDIA National Laboratories to contribute to the validation of Molybdenum in thermal energy spectrum. It supplements the study carried out in the CED-1 report by providing a more precise design of the proposed experiments and presents a complete evaluation of the experimental uncertainties. In the CED-1 report, corresponding to the preliminary design of the experiments, IRSN identified several promising configurations that could be implemented in the SPRF/CX facility of SNL. They use metallic molybdenum either in the form of foils between the UO_2 pellets inside BUCCX rods, or in the form of sleeves surrounding 7uPCX rods.

In this CED-2 report, a new design using molybdenum sleeves surrounding BUCCX rods is also analyzed and the experimental uncertainties of all the proposed configurations are estimated. Given the constraints to carry out the experiments and the costs associated with the manufacturing of the foils, the experiments using molybdenum foils are discarded. Similarly, the design using molybdenum sleeves around BUCCX rods leads to significant manufacturing costs which could certainly be partially offset by use of existing grids but which would lead to slightly lower values

of the integral sensitivities to the cross sections of molybdenum. Consequently, the design using molybdenum sleeves around 7uPCX rods is favored insofar as it presents higher k_{eff} sensitivities to the molybdenum cross sections and that there is still possibility to reduce the number of sleeves to reduce the cost of experiments. Regarding feedback on nuclear data in support of criticality-safety assessment, one of the advantages of the work described here is that the proposed experiments are not correlated with the MIRTE and FP experiments using molybdenum. In addition, they lead to higher sensitivity values in the thermal energy range than the existing experiments and partly “cover” the first resonance of the ^{95}Mo, which is a real advantage for improving knowledge on molybdenum cross sections.

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CONTEXT

This work was carried out in the framework of the PRINCESS research project [1] (PRoject for IRSN Neutron physics and Criticality Experimental data Supporting Safety), which aims at gathering and exploiting experimental data for criticality safety and reactor physics.

In 2014, a Memorandum of Understanding was signed between DOE-NNSA (Department of Energy of the United States of America - National Nuclear Security Administration) and IRSN, allowing a framework for collaborations with USA laboratories within the Nuclear Criticality Safety Program (NCSP). This memorandum was extended in 2016 for four years.

The Mo-SNL program arises from a French established criticality safety data need for molybdenum cross sections validation. An Integral Experiment Request (IER n°305) was established and it was decided that IRSN would lead the design of critical experiments to meet this data need.

For this IER, IRSN collaborates with the Sandia National Laboratories (SNL) that operated the SPRF/CX facility.

The pre-design report (CED[a]-1 [2]) proposed various designs for consideration; the financial aspects were partly taken into account since it was reviewed due to the manufacturing cost of molybdenum sleeves. This CED-2 report completes the CED-1 report [2] providing with a more refined definition of experiments. Additional experiments are proposed to address a new configuration requested by the CED team and involving Mo sleeves around BUCCX rods (as in the experiments with titanium performed in 2018 and referred as to LCT-099 in ICSBEP handbook) and also to address moderation ratio issues as well as “reference” experiments without material. Moreover, a detailed assessment of the experimental uncertainties is provided.

1 INTRODUCTION

Molybdenum isotopes are currently encountered in irradiated fuel as fission products or in molybdenum alloys in research reactors, space reactors (UMo slabs). Moreover, in the nuclear cycle, it can be taken into account in criticality safety studies for transport casks or irradiated fuel storage (use of burn-up credit) or in reprocessing plants (UPu-MoZr deposits in reprocessing plants equipment for example).

Thus, accurate nuclear data of molybdenum isotopes in a wide energy range are important. Few quality experiments with a sufficiently high reactivity worth and sensitivity of ^{95}Mo to capture are available in the literature. The objective of new experiments involving molybdenum is:

- To increase the sensitivity of k_{eff} to the capture of ^{95}Mo in thermal energy spectrum,
- To dispose of a new set of experiments that will not be correlated with the existing thermal experiments, allowing a better feedback on nuclear data.

The proposed experiments are the subject of IER-305 and take part within the IRSN PRINCESS project [1].

Design calculations that follow are based on the assumption of pure natural molybdenum. This is why technical specifications will target at least 99 % pure molybdenum avoiding impurities such as Fe, Cr, Ni, W, Pb, In, Hf, Ga, Gd, Cd, Re and W. The purchased Mo could follow the ASTM B387 standard (Molybdenum 361 and 365). In addition, chemical characterization of the Mo sleeves with ICP-MS or GDMS techniques will ensure that the amount of impurities is precisely known.

[a] CED means Critical subcritical Experiment Design.

2 FEASIBILITY STUDY

2.1 Reminding of configurations presented in the CED-1 report

The aim of the CED-1 report [2] was to study a wide range of possible experiments that could be run in SPRF/CX. Finally, analysing the various tested configurations, two main designs were retained involving molybdenum either in foils inside BUCCX rods between the UO_2 pellets or taking the shape of sleeves stuck onto the 7uPCX rods, the sleeves allowing having higher sensitivities to Molybdenum data.

The characteristics of the two retained designs are reminded in Table 1 below and in Figure 3 to Figure 6. The k_{eff} and integral sensitivities to the total cross section of ^{95}Mo were calculated with the 238-group SCALE 6.1 package using the ENDF/B-VII.0 library in the CED-1 report [2]. They have been recalculated with the MORET 5.C.1 Monte Carlo continuous energy code [3] using the ENDF/B-VII.0 library in this report. Calculations results are reported in Table 2.

Table 1: Main characteristics of experiments proposed in the CED-1 report.

Configurations	Type of UO_2 rods	Total Number of UO_2 rods (BUCCX or7uPCX)	Number of BUCCX rods with foils or 7uPCX rods with sleeves	Number of foils per rod	Thickness of foils or sleeves (cm)	Type of pitch/Half Pitch (cm)
18 x 18_144 ***(see** Figure 3**)***	BUCXX	324	144	23	0.578	Square/1.01
7uPCX_547sleeves_18crowns ***(see** Figure 5**)***	7uPCX	919	547		0.112	Hex/0.783

Table 2: Integral Sensitivity to ^{95}Mo total cross section for the experiments proposed in the CED-1 report.

Configurations	SCALE 6.1 238-group ENDF/B-VII.0		MORET 5.D.1 Continuous energy ENDF/B-VII.0	
	k_{eff} ± 0.00030	**Integral sensitivity (%/%)**	**k_{eff} ± 0.00030**	**Integral sensitivity (%/%)**
18 x 18_144	1.02200*	-0.0386	1.01220*	-0.0376
7uPCX_547sleeves_18crowns	1.00118	-0.10059	1.00183	-0.1007

* The discrepancy between the SCALE 6.1 and MORET 5 calculation is mainly due to the self-shielding treatment of foils between pellets associated with the multi-group SCALE 6.1 code.

Regarding the 7uPCX_547sleeves_18crowns experiment, in order to easily insert the rods inside the sleeves, a small gap is needed. As it was not considered in the CED-1 report, additional calculations were performed to study the impact of a realistic gap.

During the phase 3 of the MIRTE program [5], which was performed at the Valduc Facility in 2013, copper and stainless steel sleeves were used around the Valduc UO_2 rods and the gap between the sleeves and the rod was about 0.025 cm. Given that the 7uPCX have lower uncertainties on their outer diameters, such a gap seems to be realistic for the 7uPCX rods. Thus, this value was retained and the gap was filled with water. A sensitivity calculation has been performed with the MORET 5 code and the ENDF/B-VII.0 evaluation to compare with the previous designed configuration. The sensitivity profiles are reported in 1a and 1b.

No significant impact (< 4 % on integral sensitivity) is observed on the total cross section of ^{95}Mo sensitivity profile and the integral sensitivity remains quite the same. Similarly, the integral sensitivity to the fission cross section of ^{235}U, nubar cross section of ^{235}U, capture cross section of ^{238}U, total cross section of hydrogen has not been modified at all. However, k_{eff} has decreased by more than 1000 pcm. As a result, it will be necessary to add few rods on the periphery to reach criticality (see section 6.1).

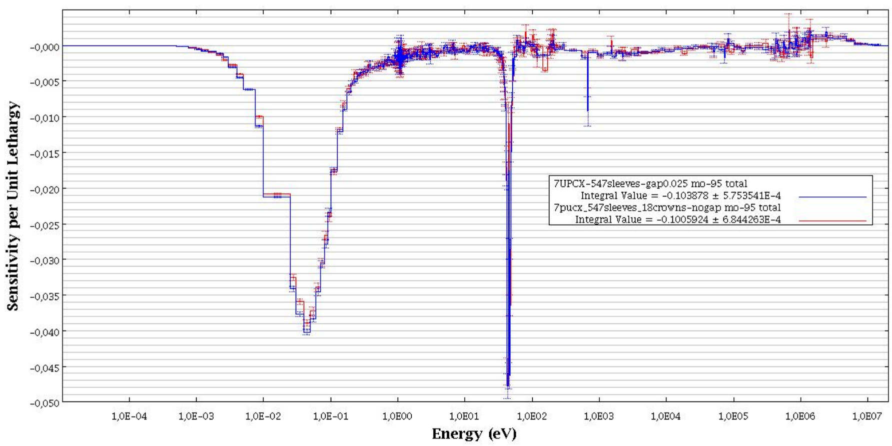

Figure 1a. Comparison of sensitivity profiles with or without gap for the 7uPCX_547sleeves_18crowns configuration – ^{95}Mo total

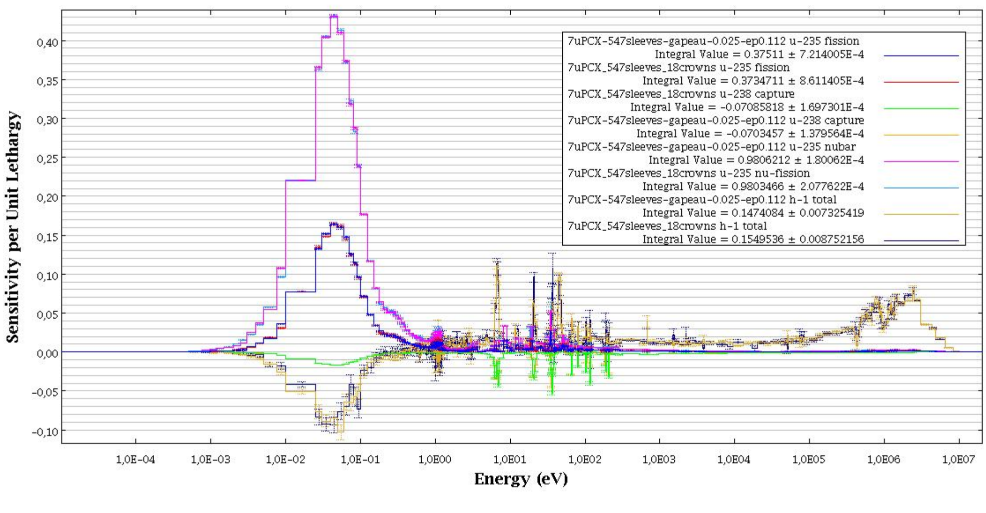

Figure 2b. Comparison of sensitivity profiles with or without gap for the 7uPCX_547sleeves_18crowns configuration – ^{235}U fission, ^{238}U capture, ^{235}U nubar, ^{1}H total

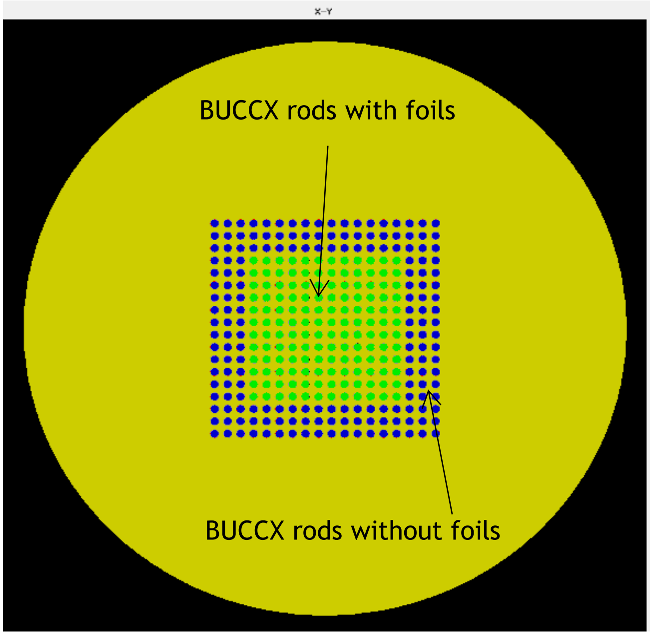

Figure 3. Cross cut view of configuration with molybdenum foils – 18 x 18_144.

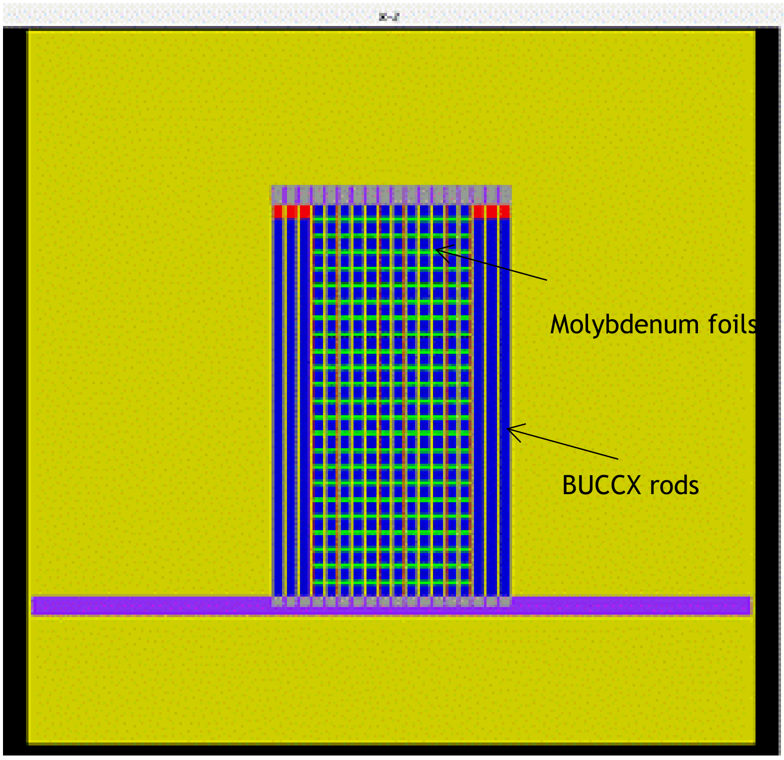

Figure 4. Vertical view of configuration with molybdenum foils – 18 x 18_144.

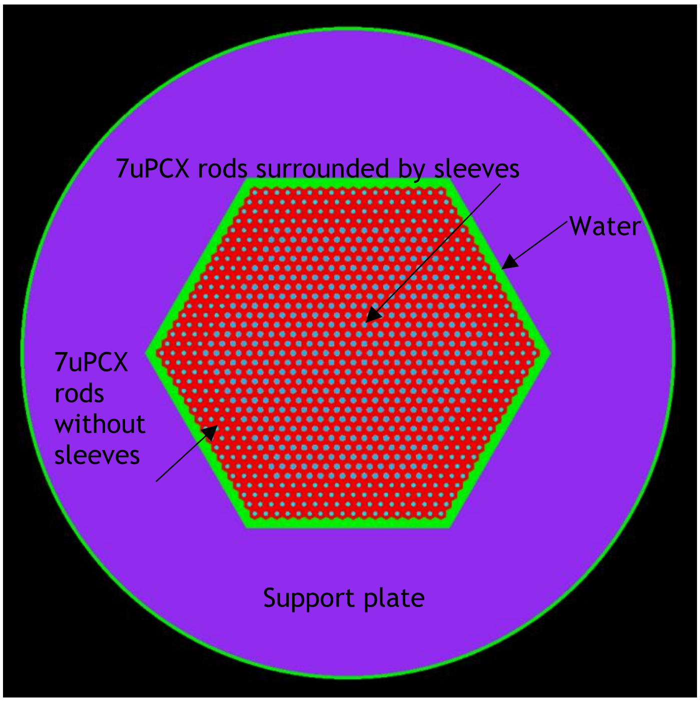

Figure 5. Cross cut view of configuration with molybdenum-sleeved 7uPCX rods at the center and 7uPCX rods without sleeves around – 7uPCX_547sleeves_18crowns.

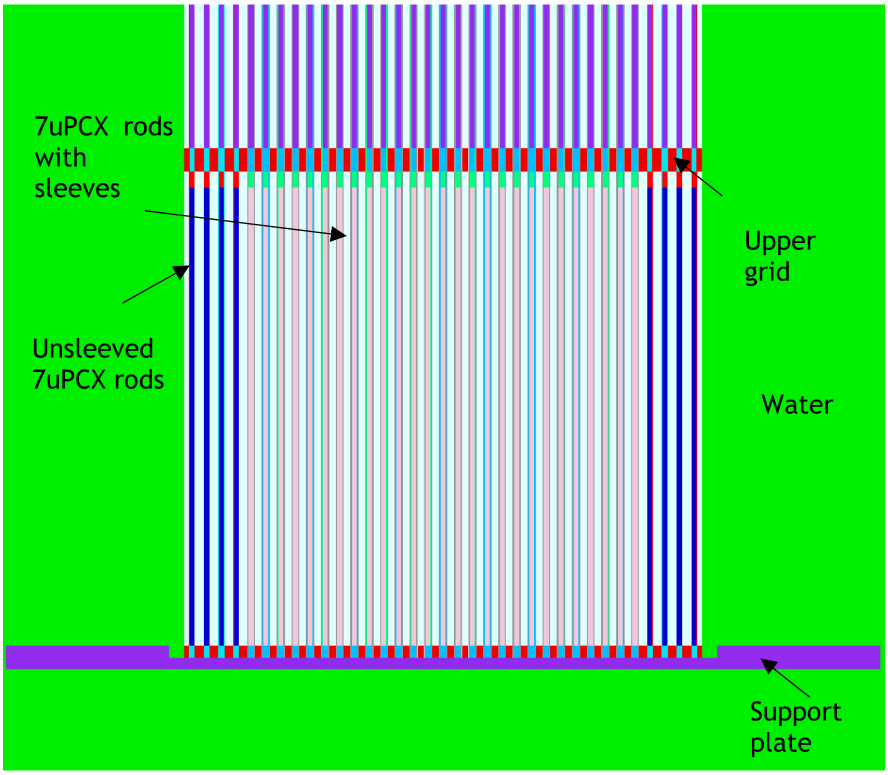

Figure 6. Vertical view of configuration with molybdenum-sleeved 7uPCX rods at the center and 7uPCX rods without sleeves around – 7uPCX_547sleeves_18crowns.

2.2 Feedback from the NCSP review group

Issues with the water gap between the 7uPCX rods and the sleeves were identified during the review of the report. With a 0.025 cm water gap, if the rods are not perfectly straight, the experimentalists pointed out a potential difficulty to fill the gap with water at the same level as in the tank. As a consequence, a larger gap must be investigated. It was shown that American suppliers could provide with sleeves having an outer diameter of 0.5 inch and a wall thickness of 0.03 inch. This configuration has been tested and optimized varying the pitch between rods and the number of rods. Finally, it was found that the optimized pitch was close to 1.6 cm. As a result and since grids with a 1.6-cm pitch were already available, the results are reported for this pitch in *Table 4*.

To reach criticality 19 crowns of UO_2 rods are necessary plus 12 additional rods to have k_{eff} slightly higher than 1 with a sufficient reactivity margin.

The characteristics of the optimized configuration are given in *Table 3*. A cross section view of the configuration is provided in *Figure 7*.

Table 3: Main characteristics of proposed design with 0.03 inch thick sleeves.

Configurations	**Type of UO_2 rods**	**Total Number of UO_2 rods**	**Number of 7uPCX rods with sleeves**	**Thickness of sleeves (cm)**	**Type of pitch/Half Pitch (cm)**
7uPCX_547sleeves_th0.03_ 1039rods_p1.6	7uPCX	1039	547	0.0762	1.6

Table 4: k_{eff} and sensitivities proposed design with 0.03 inch thick sleeves.

Configurations	**K_{eff} ± σ**	**Integral sensitivity to ^{95}Mo total cross section**	**Type of pitch/Half Pitch (cm)**
7uPCX_547sleeves_th0.03_ 1039rods_p1.6	1.00463 ± 0.00020	-0.0976	1.6

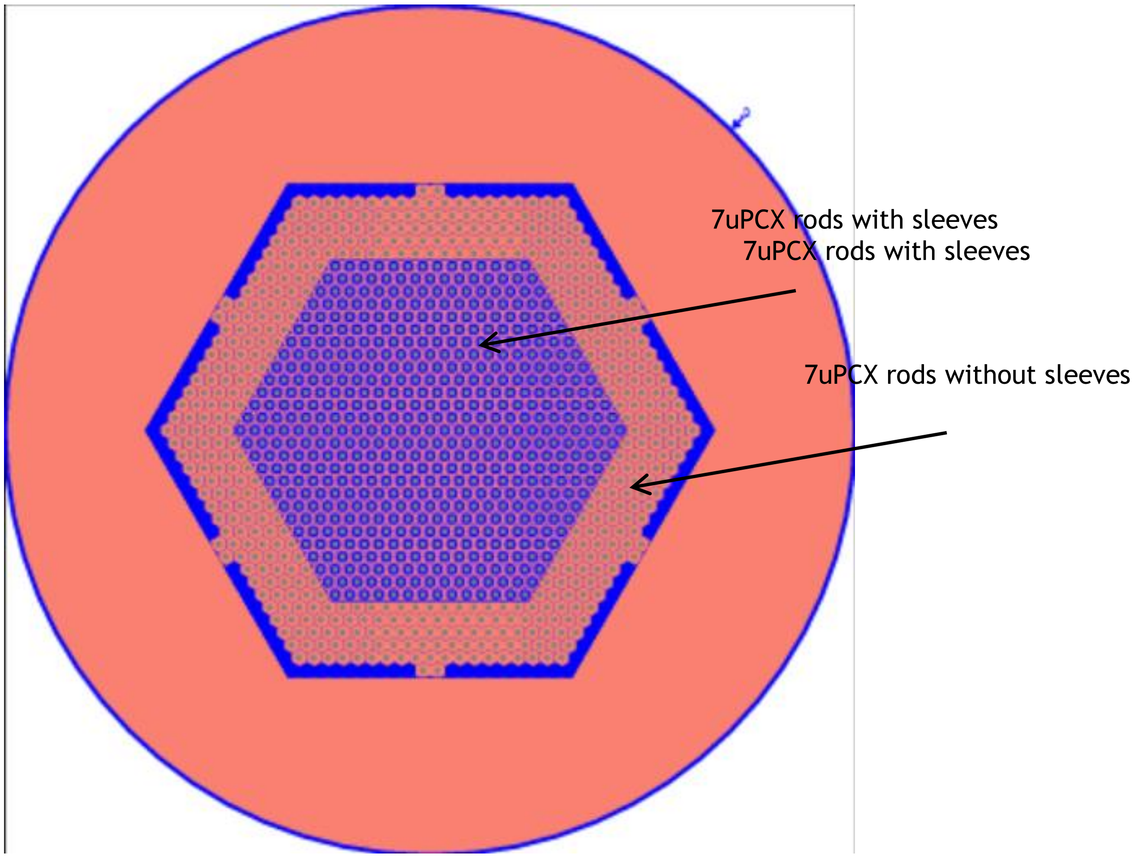

Figure 7. Cross section view of the optimized configuration with 0.0762-cm thick sleeves.

2.3 Feasibility of others configurations

In LEU-COMP-THERM-099, titanium and aluminum sleeves were adapted around BUCCX rods. As a consequence, we know that such sleeves can be manufactured and we can benefit from the experience of Sandia on such design. Therefore, it was decided to study configurations involving Molybdenum sleeves around BUCCX rods and to fix the cladding/sleeve gap at the same value as for LEU-COMP-THERM-099 (0.49 cm). Moreover, two options were considered for the chemical medium filling the gap: either air or water. The option with air filling the gap cladding/sleeve was quickly discarded because criticality could not be reached with the available rods.

The choice of the configuration was based on the optimization of k_{eff} sensitivity to total cross section of ^{95}Mo. Various designs were tested alternating 7uPCX rods without sleeves and BUCCX rods surrounded by molybdenum sleeves in the central lattice. The ECEGO algorithm of PROMETHEE tool [7] was used for that task with the MORET 5.C.1 code and the associated ENDF/B-VII.0 library. The varying parameters were the number of 7uPCX and BUCCX rods, the pitch between rods, which is taken as being the same all over the lattice, the thickness of molybdenum sleeves. The variation range of the thickness of sleeves is set between 0 and 0.325 cm. The hexagonal pitch is comprised between 1.6 and 2.8 cm. All the results are gathered in Table 5.

A cross cut view of the sensitivity profiles is given in Figure 8. It can be seen that there is no significant impact of the pitch and the number of 7uPCX in the driver lattice on the shape of the sensitivity profile.

A cross cut view of the configurations is provided in Figure 9 to Figure 10.

Table 5: Design of configurations with molybdenum sleeves.

<table>
<tr><th rowspan="2">Configuration</th><th rowspan="2">Number of BUCCX rods with sleeves</th><th rowspan="2">Total Number of rods (BUCCX + 7uPCX)</th><th rowspan="2">Optimal Thickness of sleeves (cm)</th><th rowspan="2">Type of pitch/ Optimal Pitch (cm)</th><th colspan="2">Research of optimal case</th><th rowspan="2">Figures</th></tr>
<tr><th>k_{eff} (+/- 0.00100)</th><th>Integral sensitivity (%/%)</th></tr>
<tr><td>181_7uPCX_216_BUCCX_hex</td><td>216</td><td>397*</td><td>0.046</td><td>2.6</td><td>1.00109</td><td>-4.02E-02</td><td>Figure 9</td></tr>
<tr><td>505_7uPCX_216_BUCCX_hex_2.6</td><td>216</td><td>721*</td><td>0.100</td><td>2.6</td><td>1.00548</td><td>-8.48E-02</td><td rowspan="3">Figure 10</td></tr>
<tr><td>505_7uPCX_216_BUCCX_hex_2.7</td><td>216</td><td>721*</td><td>0.090</td><td>2.7</td><td>1.00609</td><td>-7.82E-02</td></tr>
<tr><td>505_7uPCX_216_BUCCX_hex_2.8</td><td>216</td><td>721*</td><td>0.077</td><td>2.8</td><td>1.00611</td><td>-6.81E-02</td></tr>
</table>

* The total number of rods is given by the following formula. Total Number of rods = 3N×(N-1)+1 where N is the number of rods on the outer edge of the hexagon.

The optimum sensitivity is obtained for a total of 505 7uPCX rods, 216 sleeved BUCCX rods, a thickness of sleeves of 0.100 cm and a hexagonal pitch of 2.6 cm. However, it should be noticed that a constraint was fixed related to the feasibility of grids maintaining the rods assembly. Feedback from previous programs involving tight packed lattices of rods performed at the Valduc facility (LEU-COMP-THERM-071) [4] showed that a thickness of 0.085 cm between grid holes was essential for the manufacturing of grids. If the same assumptions regarding the gap rods/grid holes are retained (0.02 cm), for a thickness of sleeves equating 0.1 cm, the pitch between rods cannot be lower than 2.69 cm. Therefore, the configuration with a pitch equal to 2.7 cm is finally retained.

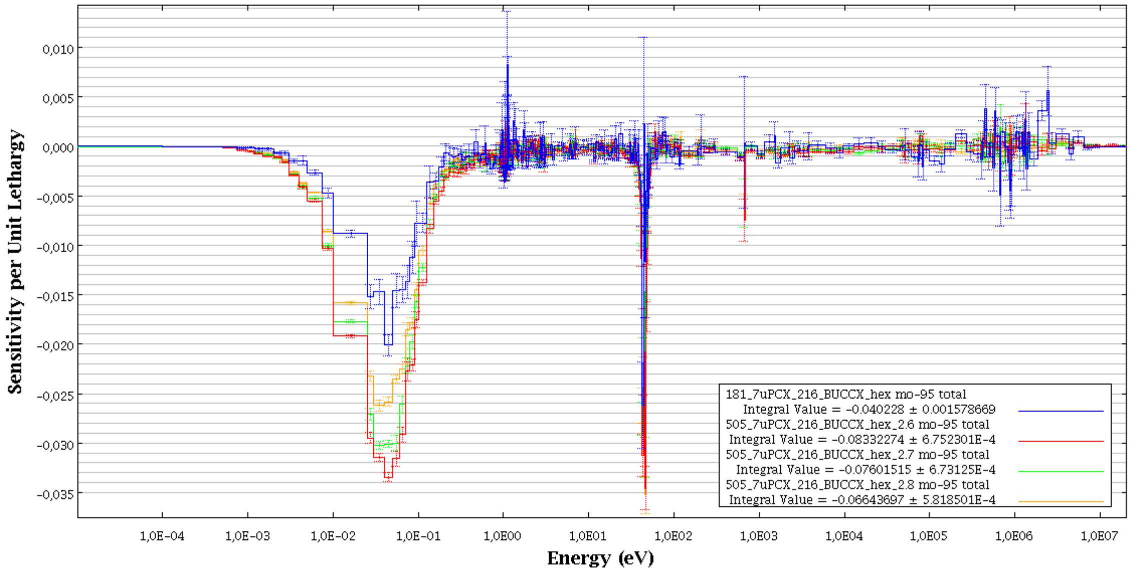

Figure 8. ^{95}Mo total cross section sensitivity profile of configurations involving Mo-sleeved BUCCX rods.

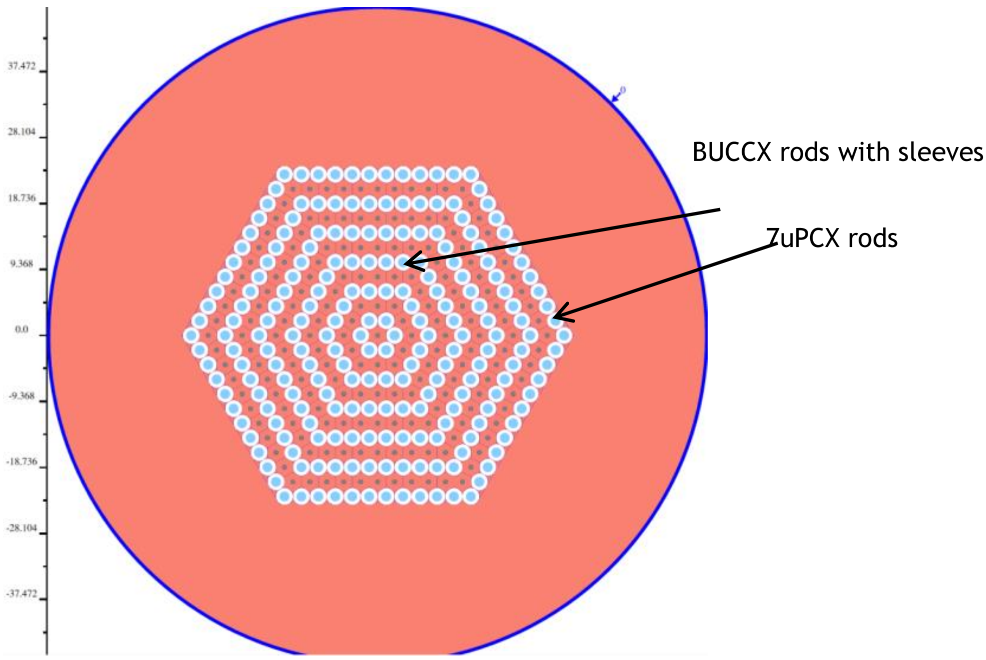

Figure 9. 181_7uPCX_216_BUCCX_hex.

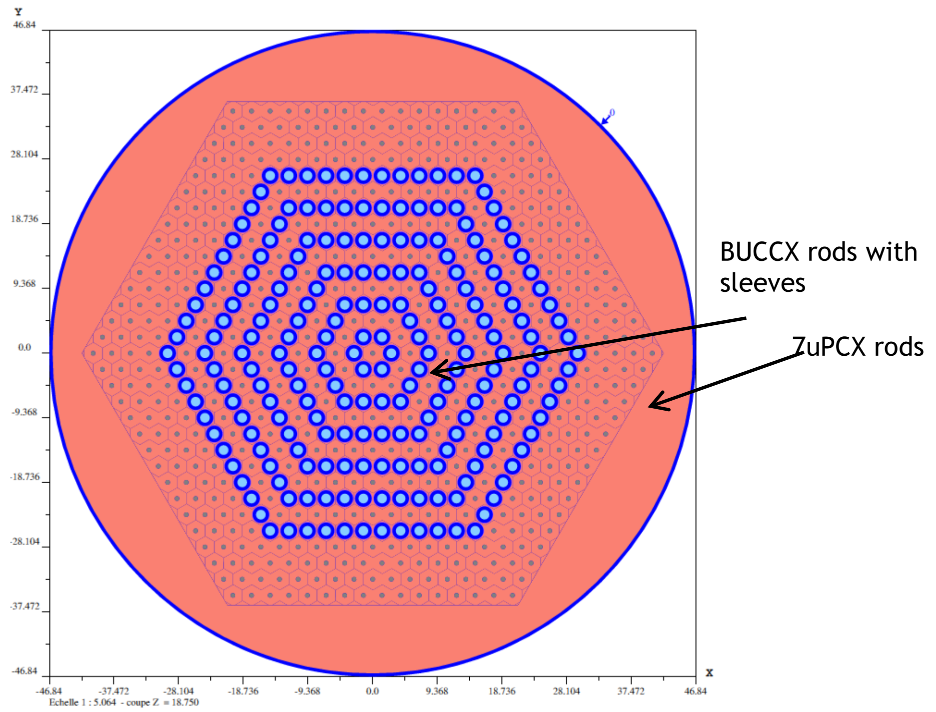

Figure 10. 505_7uPCX_216_BUCCX_hex.

2.4 Comparison with cases of interest

2.4.1 Comparison with French experiments

The sensitivity profiles of the designed experiments are compared with two French experiments (see Figure 11):

- PF-2948, involving a test sandwich of CH_2/Mo surrounded by a driver lattice of Valduc UO_2 rods,
- The MIRTE 4A-Mo-010 experiment involving a 10-mm screen of molybdenum between four lattices of Valduc UO_2 rods. The configuration is described in [5].

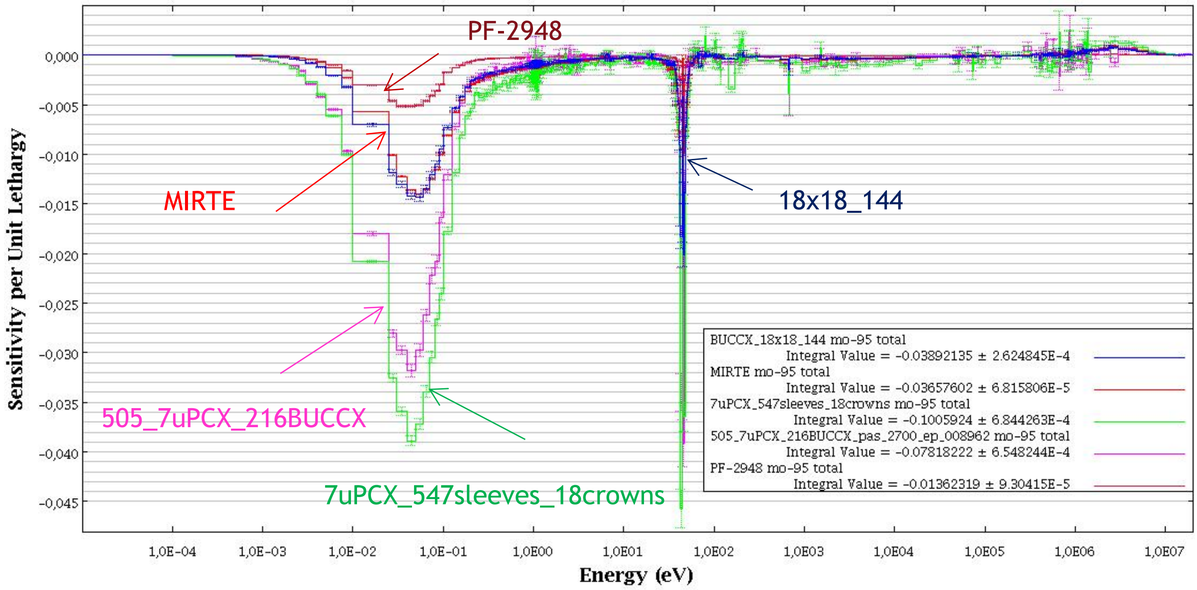

Figure 11. ^{95}Mo total cross section sensitivity profiles of designed configurations involving Mo compared with MIRTE and PF French experiments.

One can see that the designed experiments are more sensitive (integral sensitivity difference > 100 %) to the total cross section of molybdenum than the previous MIRTE and PF-2948 experiments realized at Valduc research center, which were constrained by the number of rods available that restrained the quantity of molybdenum that could be added while remaining critical.

This is particularly true at the thermal bump but also at the first resonance peak of ^{95}Mo. Moreover, the shape of the sensitivity profiles remains quite similar.

2.4.2 Comparison with application cases

A comparison is first performed with an UPuMoZr application case featuring molybdenum residues in a French reprocessing plant dissolvor. The residues composition that is taken into account in criticality safety calculations is provided in Table 6. The density of the UPuMoZr compound is 2.6 g/cm^3. The isotopics of Molybdenum is given in Table 7. It is assumed to be representative of a fuel burnt at a burnup of 50 GWd/t heavy metal. The sensitivity profiles of the designed optimized cases and the application case are reported in Figure 12.

Table 6 : Composition of UPuMoZr residues.

Element	U	Pu	Mo	Zr
Contents in wt. %	6.06	2.43	63.40	28.11
Isotope	^{235}U	^{238}U		
Enrichment in wt. %	1	99		
Isotope	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Content in wt. %	57.2875	25	16.25	1.4625

Table 7 : Isotopics of Molybdenum.

Isotope	^{92}Mo	^{95}Mo	^{96}Mo	^{97}Mo	^{98}Mo	^{100}Mo
Contents in wt. %	1	21	3	23	25	27

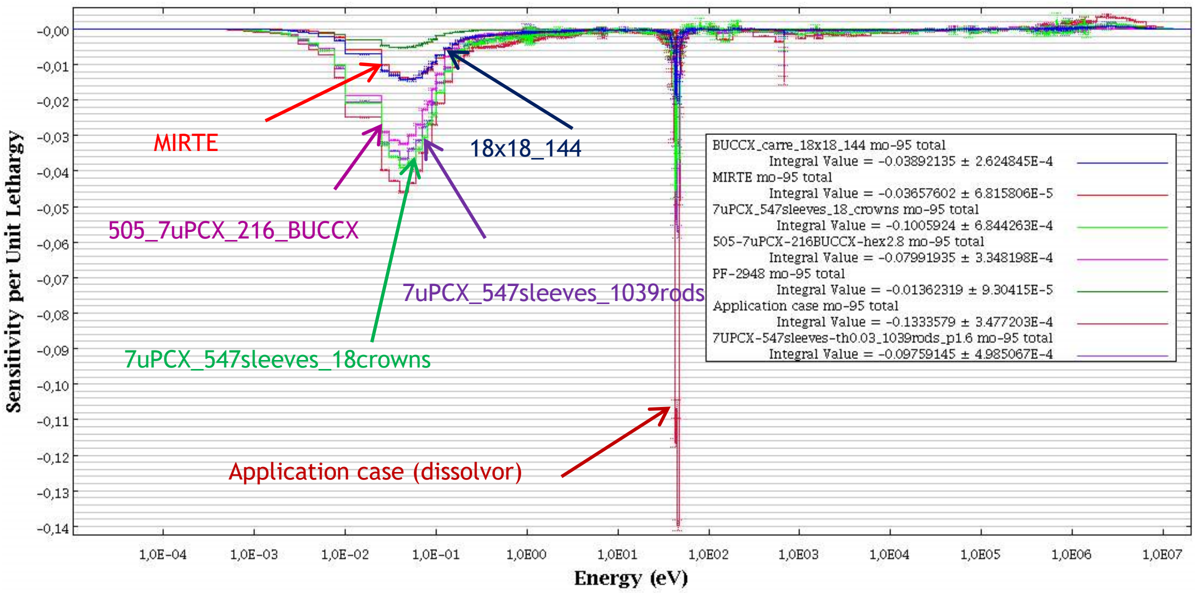

Figure 12. ^{95}Mo total cross section sensitivity profile of designed configurations compared with French application case (Dissolvor).

One can see from *Figure 12* that the experiments with molybdenum-sleeved rods (7uPCX_547sleeves_18crowns and 505_7uPCX_216BUCCX) at a hexagonal pitch are very close from the industrial case in terms of shape of sensitivity profile and value of integral sensitivity of k_{eff} to the total cross section of ^{95}Mo. However, the amplitude of the sensitivity at the first resonance of ^{95}Mo is a bit higher for the industrial case (27 % discrepancy).

The second application case consists in an infinite storage of baskets hosting 9 cells (see Figure 14). The cells, made of borated steel, contain standard 17 × 17 UO_2 spent fuel assemblies. The central assembly is considered as being in maximum expansion. The assemblies are assumed to have been irradiated up to 30 GWd/t and then cooled during a 90 days period. The irradiation conditions were chosen so that a conservative composition of the fissile medium was obtained. A cross cut view of the configuration is given in Figure 14. It can be seen that some assemblies are not centered in the canisters.

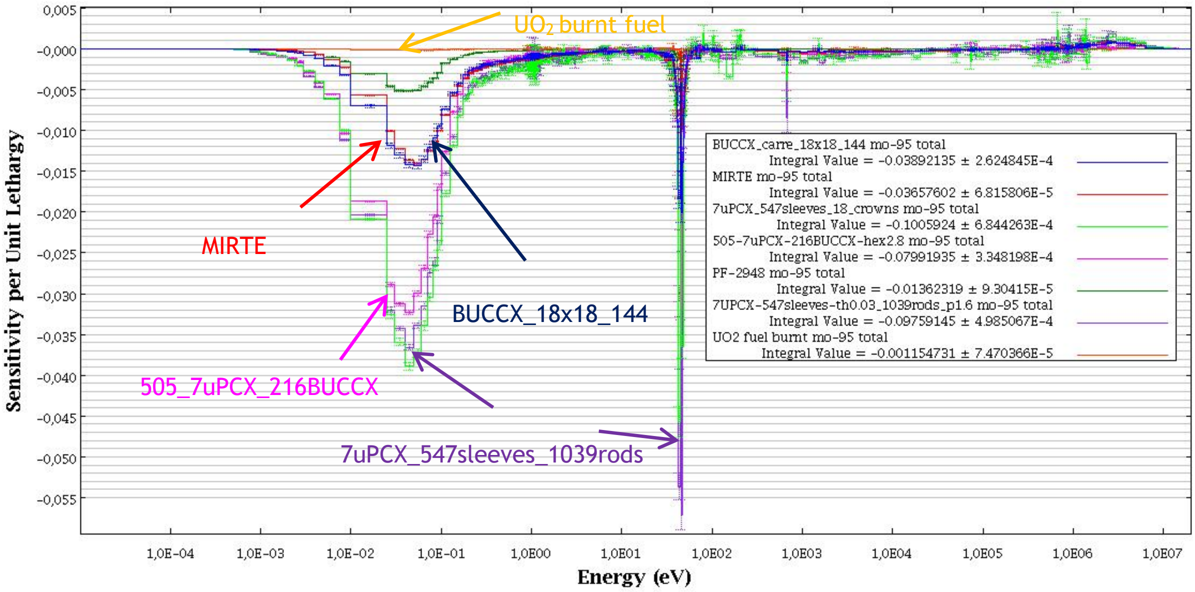

Figure 13. ^{95}Mo total cross section sensitivity profiles of designed configurations involving Mo compared with an industrial case involving burnt UO_2 fuel.

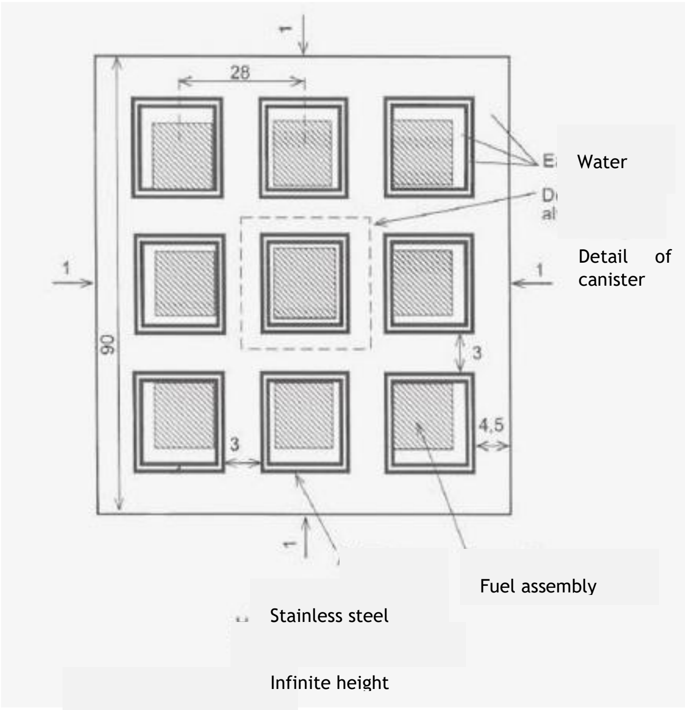

Figure 14. Application case with UO_2 burnt fuel.

In that case, for the various presented experiments, k_{eff} is far more sensitive to the total cross section of ^{95}Mo than for the application case involving burnt UO_2 fuel (see Figure 13) by a factor of nearly 100.

2.5 Feedback on nuclear data

A SCALE 6.2 calculation [6] using the ENDF/B-VII.0 and ENDF/B-VII.1 libraries and their associated 44-energy-group and 56-energy-group covariance libraries (see Figure 15) and the SAMS module allowed determining the propagated uncertainty of nuclear data for the experiment with 7uPCX sleeved rods (7uPCX_547sleeves_18crowns) and with 505_7uPCX_216_BUCCX_hex_2.7.

One can see in Table 8 and in Table 9 that the main propagated uncertainties come from the nubar of ^{235}U, the chi of ^{235}U and the capture cross sections of ^{95}Mo. As a result, feedback on molybdenum cross sections whose uncertainty can reach 20 % in the thermal energy range could be retrieved from the experiments.

Table 8: Prior uncertainties due to nuclear data for 7uPCX_547sleeves_18crowns.

Reaction	**Propagated Δk_{eff} +/- Uncertainty**	**Reaction**	**Propagated Δk_{eff} +/- Uncertainty**
	ENDF/B-VII.1		ENDF/B-VII.0
u-235 nubar	3.7072E-01 ± 9.7575E-05	u-235 nubar	2.9525E-01 ± 7.1032E-05
u-235 chi	3.6569E-01 ± 1.4619E-03	u-235 chi	2.2119E-01 ± 6.3502E-04
mo-95 n,gamma	2.1179E-01 ± 4.4313E-05	**mo-95 n,gamma**	2.1883E-01 ± 5.5966E-05
h-1 n,gamma	1.8021E-01 ± 1.2308E-05	h-1 n,gamma	8.4548E-02 ± 3.0438E-06
mo-96 n,gamma	1.6730E-01 ± 3.5942E-05	mo-96 n,gamma	1.5344E-01 ± 4.2668E-05
u-235 n,gamma	1.6337E-01 ± 1.6386E-05	u-235 n,gamma	1.6466E-01 ± 1.8526E-05
u-238 n,n'	1.2742E-01 ± 5.1151E-04	u-238 n,n'	1.2588E-01 ± 5.2548E-04
mo-97 n, gamma	1.2602E-01 ± 9.7949E-05	mo-97 n, gamma	1.2286E-01 ± 8.0568E-05
u-235 fission	1.2565E-01 ± 3.3223E-05	u-235 fission	1.2587E-01 ± 3.8074E-05
h-1 elastic	1.1629E-01 ± 7.6191E-05	h-1 elastic	2.1355E-01 ± 2.8041E-04
o-16 elastic	1.1057E-01 ± 2.0168E-04	o-16 elastic	8.5493E-02 ± 1.7272E04
u-238 n, gamma	9.8392E-02 ± 6.2913E-06	u-238 n, gamma	9.7253E-02 ± 1.0474E-05
mo-94 n, gamma	2.3171E-02 ± 4.3941E-07	mo-94 n, gamma	2.5182E-02 ± 8.0611E-07
u-238 nubar	2.3117E-02 ± 4.1490E-06	u-238 nubar	2.2917E-02 ± 3.7865E-06
mo-98 n, gamma	2.0221E-02 ± 3.4877E-06	mo-98 n, gamma	2.1574E-02 ± 3.4746E-06
mo-98 n, n’	1.8468E-02 ± 2.3140E-05	mo-98 n, n’	1.1435E-02 ± 9.8680E-06
u-238 chi	1.8358E-02 ± 3.0396E-05	u-238 chi	5.3724E-03 ± 2.5444E-06
mo-95 elastic	1.7971E-02 ± 5.1319E-05	mo-95 elastic	1.2381E-02 ± 3.7574E-04

Table 9: Prior uncertainties due to nuclear data for 505_7uPCX_216_BUCCX_hex_2.7.

Reaction	**Propagated Δk_{eff} +/- Uncertainty**	**Reaction**	**Propagated Δk_{eff} +/- Uncertainty**
	ENDF/B-VII.1		ENDF/B-VII.0
u-235 nubar	3.6963E-01 +/- 8.2016E-05	u-235 nubar	2.9515E-01 +/- 6.1052E-05
h-1 n,gamma	2.4969E-01 +/- 1.7502E-05	**mo-95 n,gamma**	1.6893E-01 +/- 2.7180E-05
u-235 chi	2.4503E-01 +/- 8.8086E-04	u-235 n,gamma	1.6034E-01 +/- 1.6422E-05
mo-95 n,gamma	1.6516E-01 +/- 2.1572E-05	h-1 elastic	1.5587E-01 +/- 1.7952E-04
u-235 n,gamma	1.5953E-01 +/- 1.4270E-05	u-235 chi	1.4846E-01 +/- 3.7469E-04
mo-96 n,gamma	1.3496E-01 +/- 1.8109E-05	u-235 fission	1.3058E-01 +/- 3.4113E-05
u-235 fission	1.3035E-01 +/- 2.9058E-05	mo-96 n,gamma	1.2364E-01 +/- 2.1174E-05
u-238 n, gamma	1.2114E-01 +/- 7.5757E-06	u-238 n, gamma	1.1928E-01 +/- 9.6137E-06
u-238 n,n'	1.0497E-01 +/- 4.2286E-04	h-1 n,gamma	1.1717E-01 +/- 4.3986E-06
mo-97 n, gamma	8.4126E-02 +/- 2.8418E-05	u-238 n,n'	1.0490E-01 +/- 4.1694E-04
h-1 elastic	7.9157E-02 +/- 5.0568E-05	mo-97 n, gamma	8.2593E-02 +/- 2.4010E-05
o-16 elastic	7.0138E-02 +/- 1.3733E-04	o-16 elastic	6.5257E-02 +/- 1.1595E-04
u-238 nubar	3.0629E-02 +/- 5.1721E-06	u-238 nubar	3.0383E-02 +/- 4.8615E-06
u-238 chi	2.0870E-02 +/- 3.2981E-05	mo-94 n, gamma	1.9252E-02 +/- 2.9062E-07
mo-94 n, gamma	1.8628E-02 +/- 2.0720E-07	mo-98 n, gamma	1.2748E-02 +/- 1.0869E-06
mo-95 elastic	1.3346E-02 +/- 2.4903E-05	mo-95 elastic	9.7079E-03 +/- 1.8434E-05
mo-98 n, gamma	1.2316E-02 +/- 1.1076E-06	u-238 chi	6.1259E-03 +/- 2.9352E-06
mo-98 n, n'	6.0633E-03 +/- 3.9936E-06	mo-98 n, n'	3.8203E-03 +/- 1.8285E-06

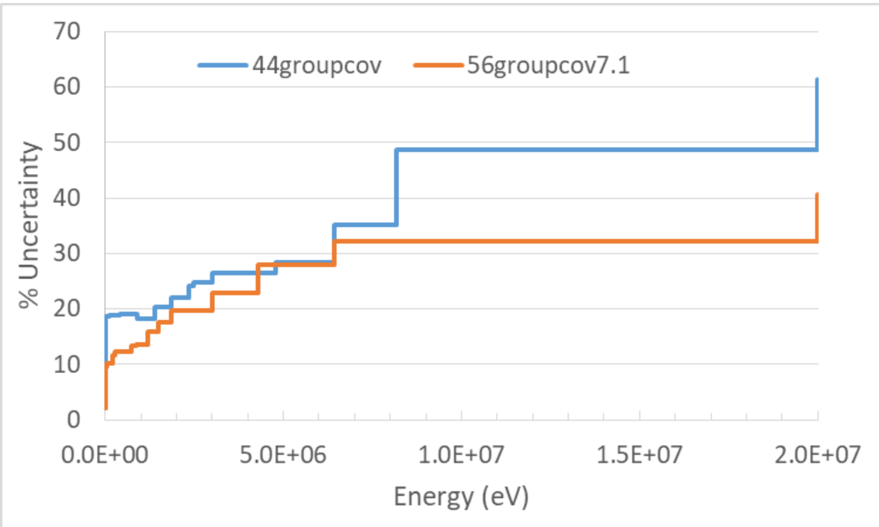

Figure 15. 56-group (ENDF/B-VII.1) and 44-group (ENDF/B-VII.0) covariance matrices of molybdenum (SCALE6.2).

3 DEFINITION OF REFERENCE EXPERIMENTS

When compared with the sensitivity of k_{eff} to the fission of ^{235}U, νbar, capture of ^{238}U, sensitivity of k_{eff} to the total cross section of ^{95}Mo can be considered as being second order of magnitude. As a result, it is necessary to discriminate it from other main sensitivities. It can be done using "reference" experiments presenting the same sensitivity of k_{eff} to the main reactions but without molybdenum. Different ways of doing can be envisioned to design them:

- Reducing the number of 7uPCX or BUCCX rods to compensate for the increase of reactivity entailed by the removal of molybdenum and remain critical,
- Reducing the water height to compensate for the increase of reactivity entailed by the removal of molybdenum.

The two methods were adopted to determine the characteristics of critical configurations with sensitivities to the main reactions close to the experiment with material.

The target configurations have been found with innovative algorithms using the PROMETHEE workbench [7] and the sensitivity capability implemented in the MORET 5.C.1 code [3] associated with the ENDF/B-VII.0 library for nuclear data. The level of water is supposed to be evaluated from the bottom of the fissile column.

The characteristics of the configurations are reported in Table 10, Table 12 and Table 13.

Sensitivity profiles to the main reactions are given in Figure 16 to Figure 17 and Figure 21 to Figure 26. Even if some discrepancy is pointed out on the sensitivity of k_{eff} to the fission of ^{235}U (about 11 %), this discrepancy being at least approximately the same order of magnitude as the sensitivity of k_{eff} to the total cross section of ^{95}Mo, it will not be a hindrance to the feedback on nuclear data. The reference experiments are therefore considered as being valid.

The reference configurations use the same name as the configurations with material, except that a "Ref" identifier is added at the beginning of the name.

In the case of molybdenum foils in BUCCX rods, it was chosen to remove the foils and suppress the air gaps between the UO_2 pellets. As a consequence, the height of the fissile column is reduced from the thickness of foils times their number in one rod. For the 0.578-cm thick foils, it gives a height reduction of 15.606 cm.

Table 10: Description of reference experiments for the **BUCCX-18 x 18_144 configuration.**

Configuration	**"Reference" case**					
	Water height from the bottom of the fissile column in cm	**Number of BUCCX rods**	**Number of rods (X/Y)**	**Pitch between rods (cm)**	**k_{eff} +/- 0.00030 (MORET 5.C.1)**	**Integral sensitivity of ^{235}U fission**
Ref-18 x 18_144	36.00	324	18/18	2.018	1.00469	2.85E-01
Ref-18 x 18_144	Fully reflected	256	16/16	2.018	1.00305	3.54E-01

In the case of molybdenum sleeves surrounding 7uPCX rods, the reference configuration is obtained removing the sleeves. The space occupied by the sleeves is therefore replaced by water along the part of fissile column height under water. It was checked that this action had sufficiently small impact on the neutron spectrum so that the sensitivity of k_{eff} to the fission of ^{235}U was not shifted in energy.

Table 11: Description of reference experiments for the **7uPCX_547sleeves_18crowns configuration.**

Configuration	"Reference" case					
	Water height from the bottom of the fissile column in cm	**Number of 7uPCX rods**	**Number of crowns***	**Pitch between rods (cm)**	**k_{eff} +/- 0.00030 (MORET 5.C.1)**	**Integral sensitivity of ^{235}U fission**
Ref-7uPCX_547sleeves_18crowns	26.00	721	16	1.566	1.00200	3.31E-01
Ref-7uPCX_547sleeves_18crowns	Fully reflected	397	12	1.566	1.03002	3.275E-01

* *Correspondence between number of crowns (N) and number of rods (n): n = (N-1)(3N-2) + 2N-1*

In order to estimate the quality of the "reference" experiments, the sensitivity profile to the total cross section of ^{95}Mo is compared to the difference of k_{eff} sensitivity to the main reactions (^{235}U fission, ^{238}U capture and ^{235}U nubar). If the sensitivity of k_{eff} to the total cross section of ^{95}Mo is the same order of magnitude or larger than the difference of k_{eff} sensitivity to the main reactions, one can hope to have a feedback on molybdenum nuclear data. The sensitivity profiles are reported in Figure 16 through Figure 17.

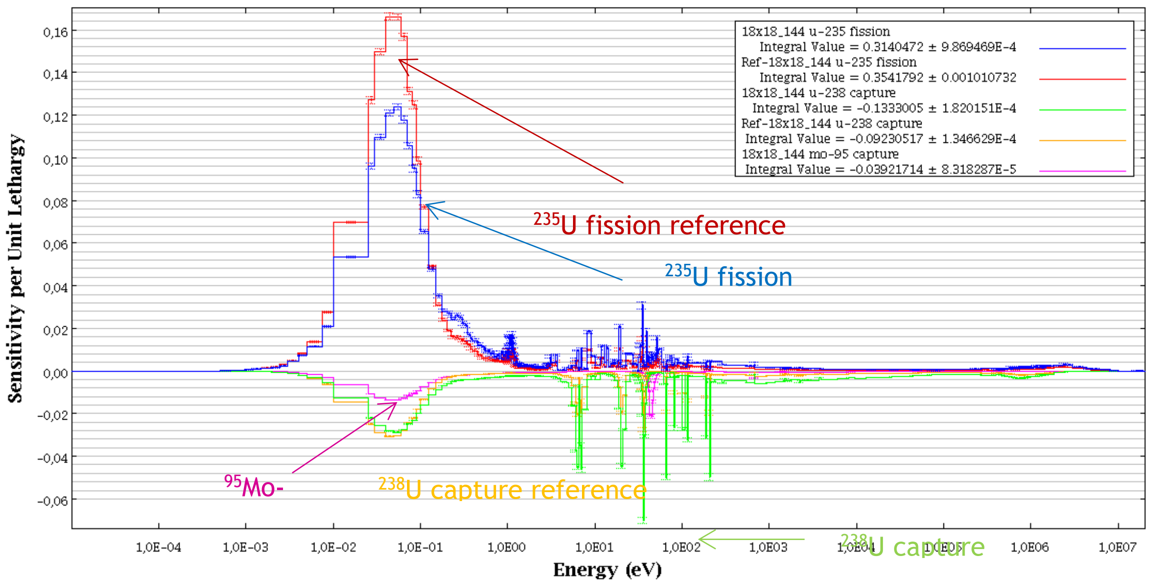

Figure 16. Comparison of sensitivity profile between experiment with ^{95}Mo foils and without (Fully reflected) -18 x 18_144 configuration.

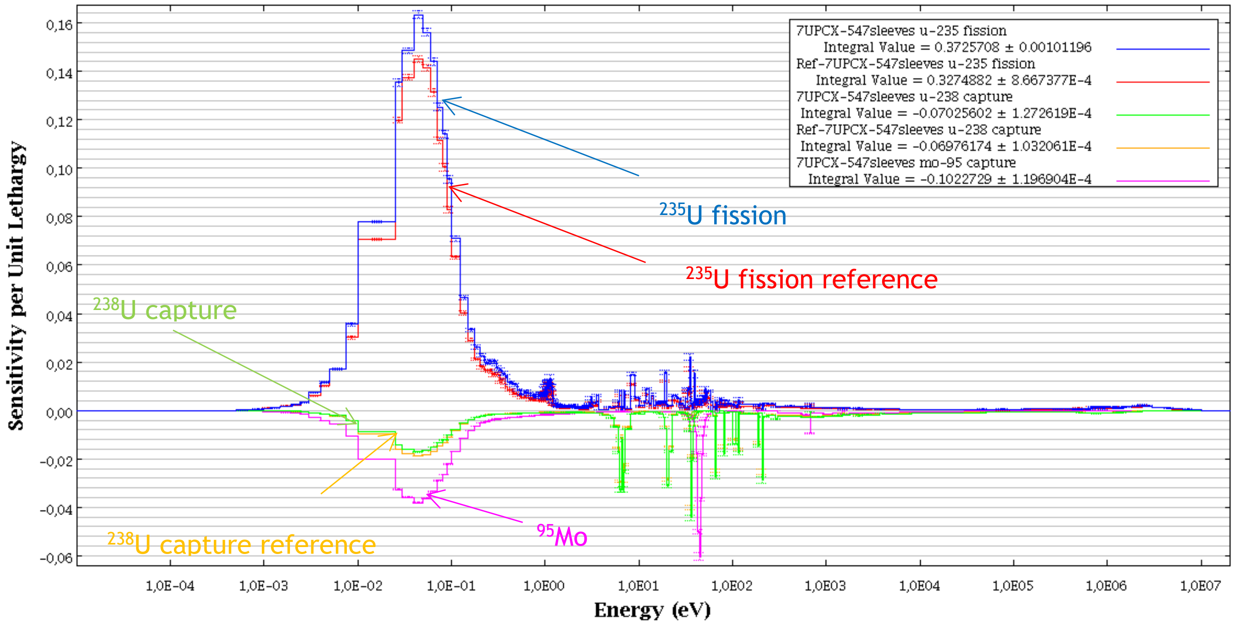

Figure 17. Comparison of sensitivity profile between experiment with ^{95}Mo sleeves and without (Fully reflected) – 7uPCX_547sleeves_18crowns (7uPCX rods).

Concerning the design involving BUCCX rods sleeved with Mo, two approaches were tested to find reference experiments:

- Replace the molybdenum sleeves surrounding the BUCCX rods with aluminium sleeves having the same thickness and optimize the pitch in order that the sensitivity of k_{eff} to the main reactions (^{235}U fission, ^{235}U nubar and ^{238}U capture) remain the same,
- Replace the molybdenum sleeves surrounding the BUCCX rods with aluminium sleeves having the same thickness and reduce the number of BUCCX rods in the lattice in order that the sensitivity of k_{eff} to the main reactions (^{235}U fission ^{235}U nubar and ^{238}U capture) remain the same.

The optimization calculations were performed using the Prométhée workbench and the MORET 5.C.1 Monte Carlo code for the transport calculation associated with the ENDF/B-VII.0 library for nuclear data.

The characteristics of the configurations are reported in Table 12 and in Figure 18 to Figure 20.

On the figures, circles in dark blue stand for the rods that have been replaced by water. Circles in light blue stand for the BUCCX rods sleeved with molybdenum. Smaller circles in dark blue stand for the 7uPCX rods which are unsleeved.

Sensitivity profiles to the main reactions are given in Figure 21 to Figure 26 for the fully reflected approach and in Figure 27 to Figure 29 for approach-to-critical by water level increase. Even if some discrepancy is pointed out on the sensitivity of k_{eff} to the fission of ^{235}U, this discrepancy being approximately the same order of magnitude as the sensitivity of k_{eff} to the total cross section of ^{95}Mo, it will not be a hindrance to the feedback on nuclear data. The reference experiments are therefore considered as being valid.

Table 12: description of the three reference experiments.

Configuration	Water height from the bottom of the fissile column in cm	Number of rods (BUCCX and 7uPCX)	Number of BUCCX rods	Pitch between rods (cm)	k_{eff} +/- 0.00050 (MORET 5.C.1)	Integral sensitivity of ^{235}U fission
Réf1-505_7uPCX_150_BUCCX_hex_2.93	Fully reflected	655	150	2.93	1.00557	0.36526
Réf2-505_7uPCX_117_BUCCX_hex_2.7		622	117	2.7	1.00411	0.35249
Réf3-505_7uPCX_144_BUCCX_hex_2.7	44	649	144	2.7	1.00497	0.35169

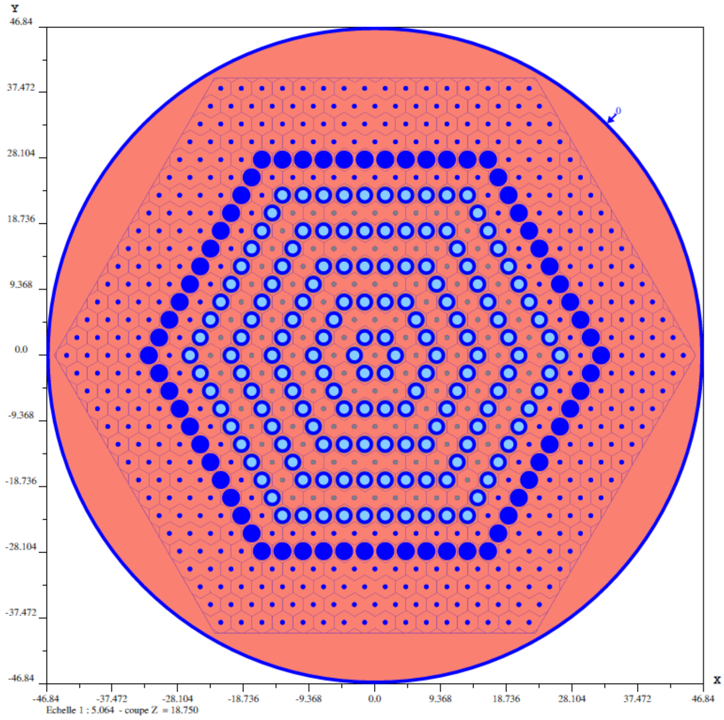

Figure 18. Cross cut view of reference experiment with ^{95}Mo sleeves replaced by Al sleeves – Fully reflected configuration – pitch = 2.93 cm – Ref1-505_7UPCX_150_BUCCX_HEX_2.93 - circles in dark blue stand for the rods that have been replaced by water. Circles in light blue stand for the BUCCX rods sleeved with molybdenum. Smaller circles in dark blue stand for the 7uPCX rods which are unsleeved.

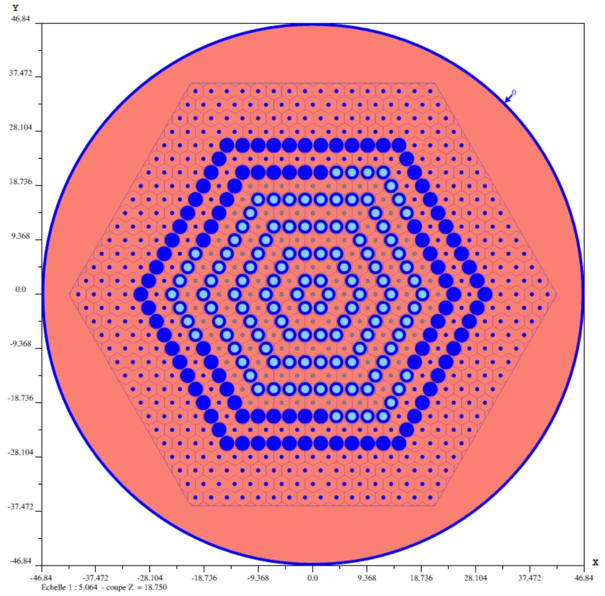

Figure 19. Cross cut view of reference experiment with ^{95}Mo sleeves replaced by Al sleeves – Fully reflected configuration pitch = 2.7 cm – Ref2-505_7UPCX_117_BUCCX_HEX_2.7 - circles in dark blue stand for the rods that have been replaced by water. Circles in light blue stand for the BUCCX rods sleeved with molybdenum. Smaller circles in dark blue stand for the 7uPCX rods which are unsleeved.

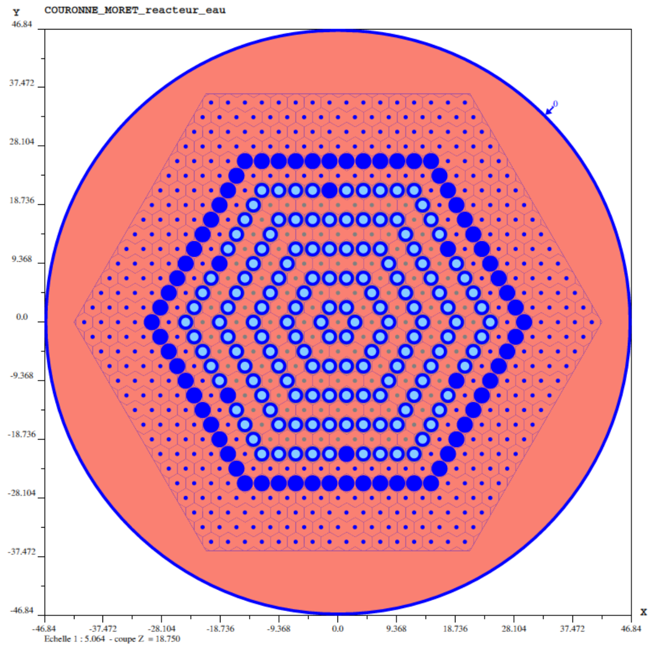

Figure 20. Cross cut view of reference experiment with ^{95}Mo sleeves replaced by Al sleeves – Increase of water level – pitch = 2.7 cm – Ref3-505_7UPCX_144_BUCCX_HEX_2.7 - circles in dark blue stand for the rods that have been replaced by water. Circles in light blue stand for the BUCCX rods sleeved with molybdenum. Smaller circles in dark blue stand for the 7uPCX rods which are unsleeved.

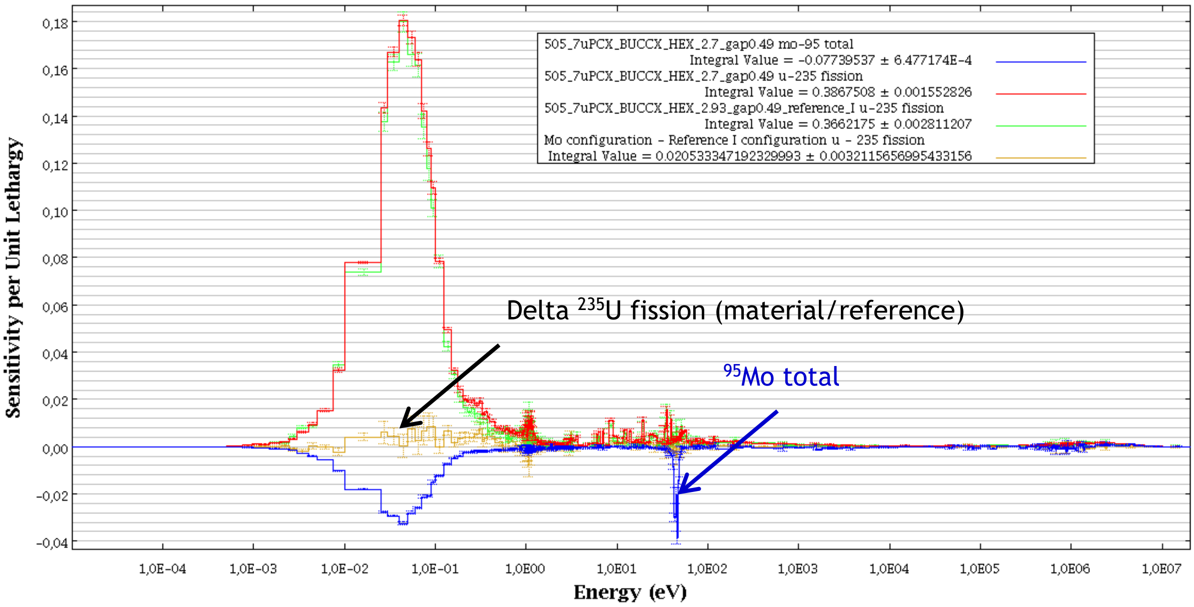

Figure 21. Sensitivity Profile of ^{95}Mo total cross section compared with difference of sensitivity for ^{235}U fission, between **505_7uPCX_216_BUCCX_hex_2.7** *experiment with molybdenum and its reference I*

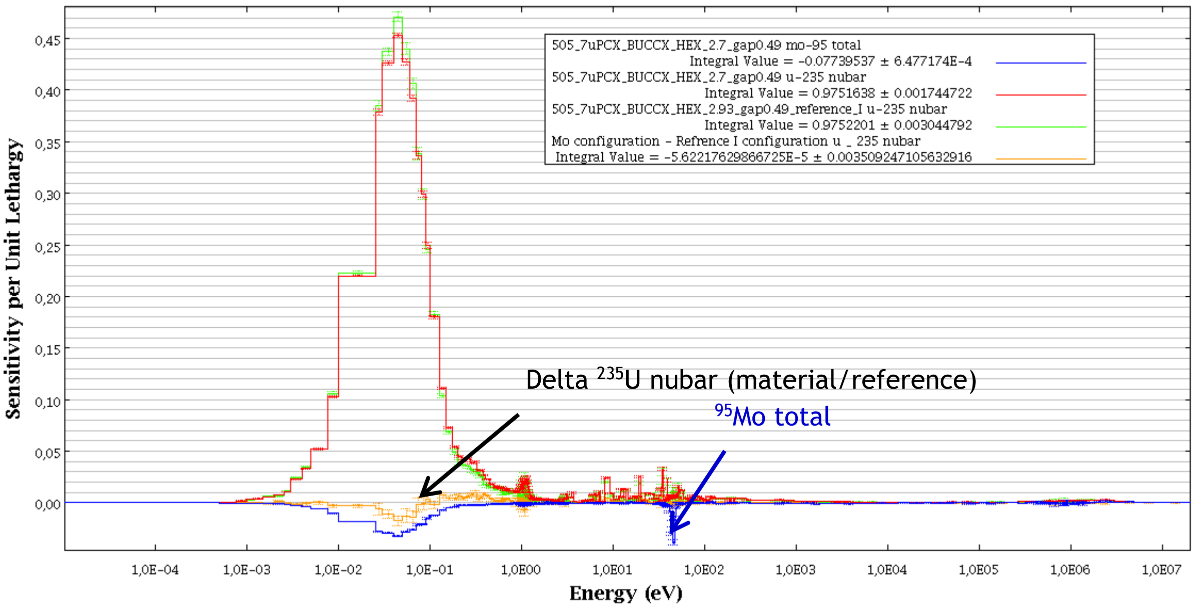

Figure 22. Sensitivity Profile of ^{95}Mo total cross section compared with difference of sensitivity for ^{235}U nubar, between **505_7uPCX_216_BUCCX_hex_2.7** *experiment with molybdenum and its reference I*

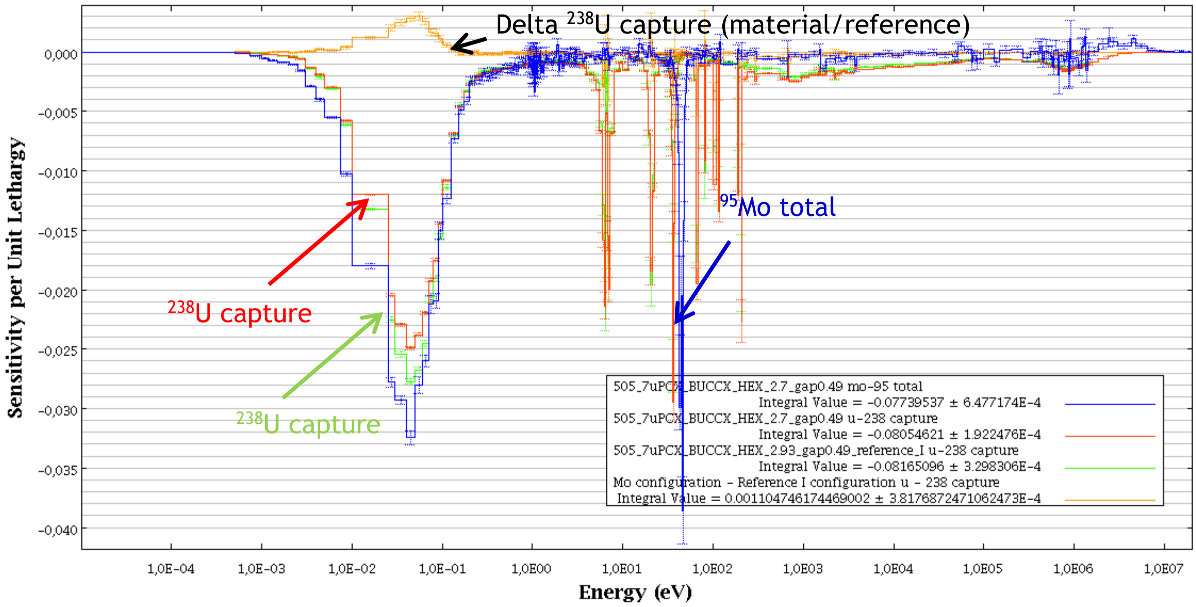

Figure 23. Sensitivity Profile of ^{95}Mo total cross section compared with difference of sensitivity for ^{238}U capture, between **505_7uPCX_216_BUCCX_hex_2.7** *experiment with molybdenum and its reference I*

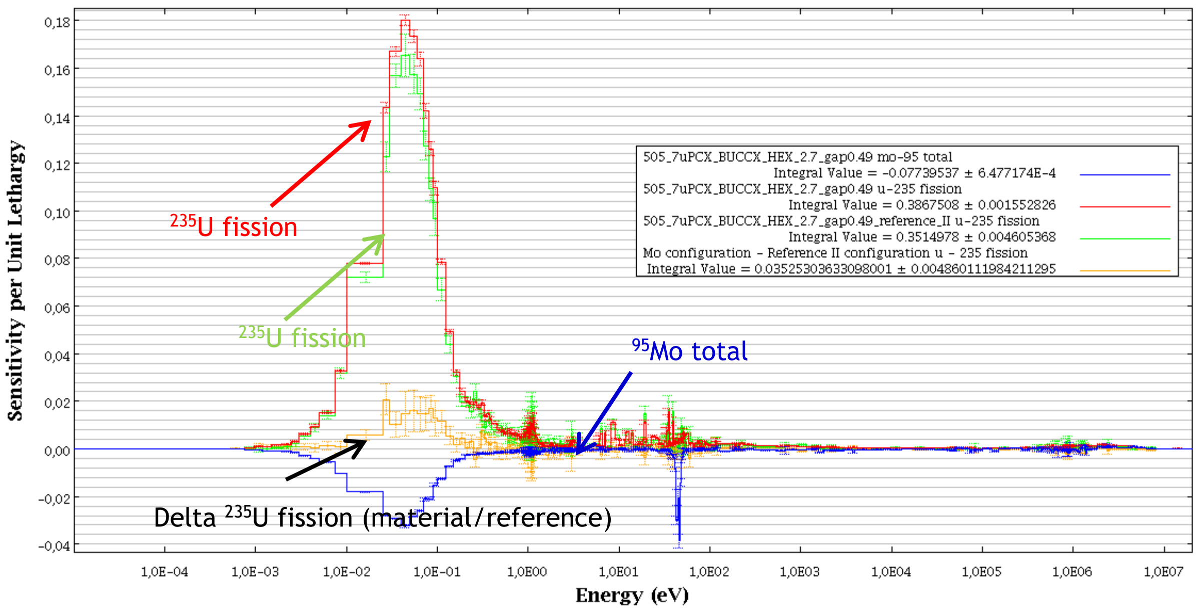

Figure 24. Sensitivity Profile of ^{95}Mo total cross section compared with difference of sensitivity for ^{235}U fission, between **505_7uPCX_216_BUCCX_hex_2.7** *experiment with molybdenum and its reference II*

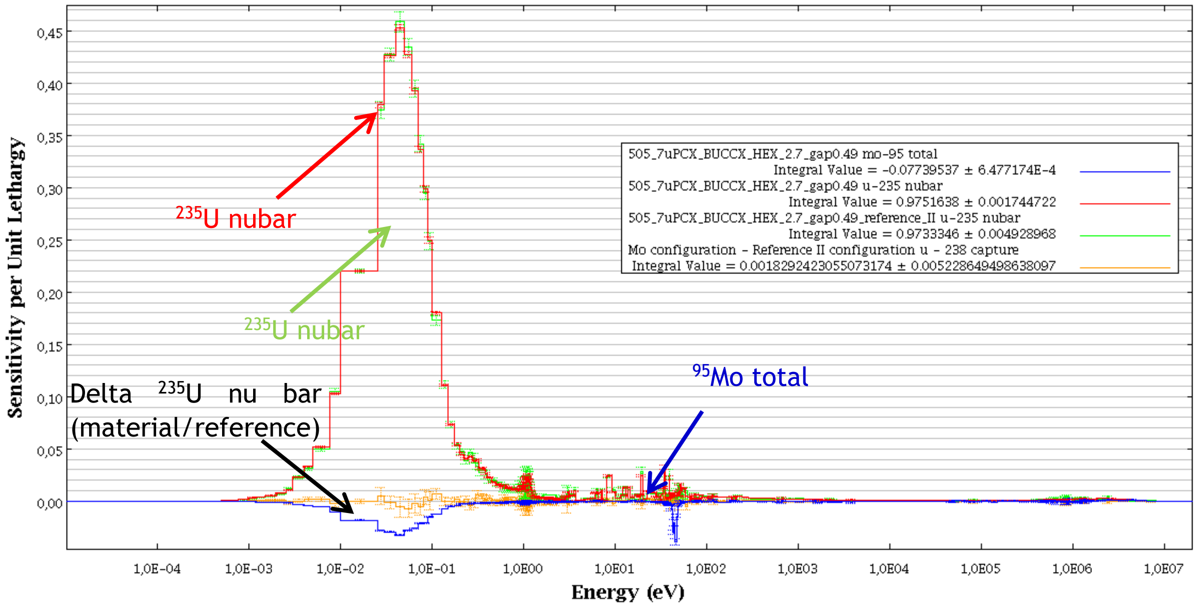

Figure 25. Sensitivity Profile of ^{95}Mo total cross section compared with difference of sensitivity for ^{235}U nubar, between **505_7uPCX_216_BUCCX_hex_2.7** *experiment with molybdenum and its reference II*

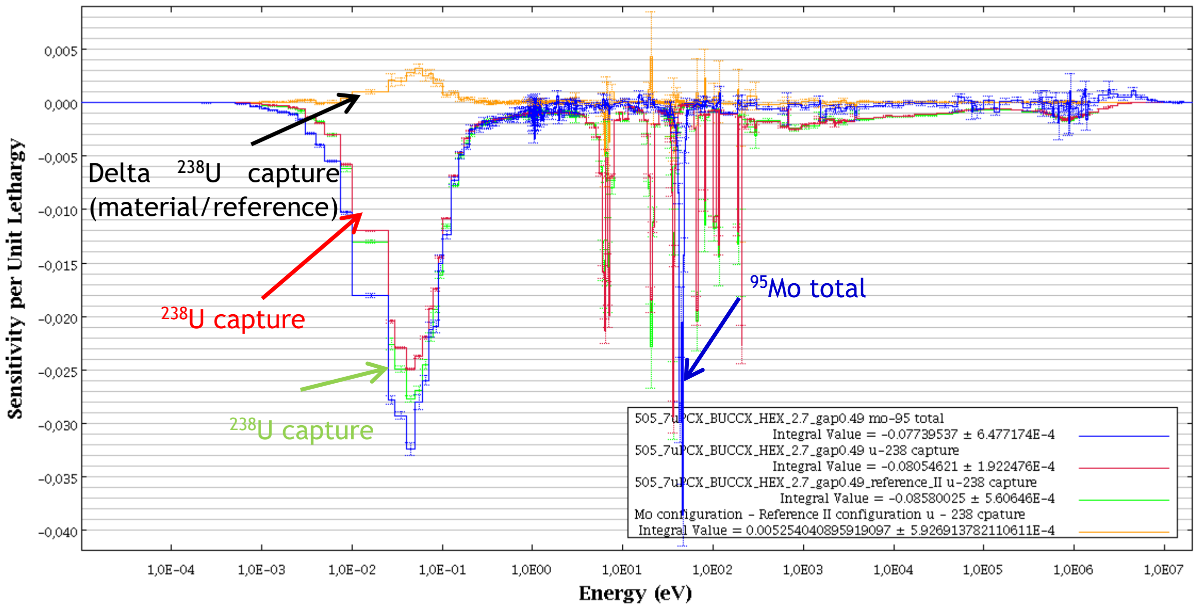

Figure 26. Sensitivity Profile of ^{95}Mo total cross section compared with difference of sensitivity for ^{238}U capture, between **505_7uPCX_216_BUCCX_hex_2.7** *experiment with molybdenum and its reference II*

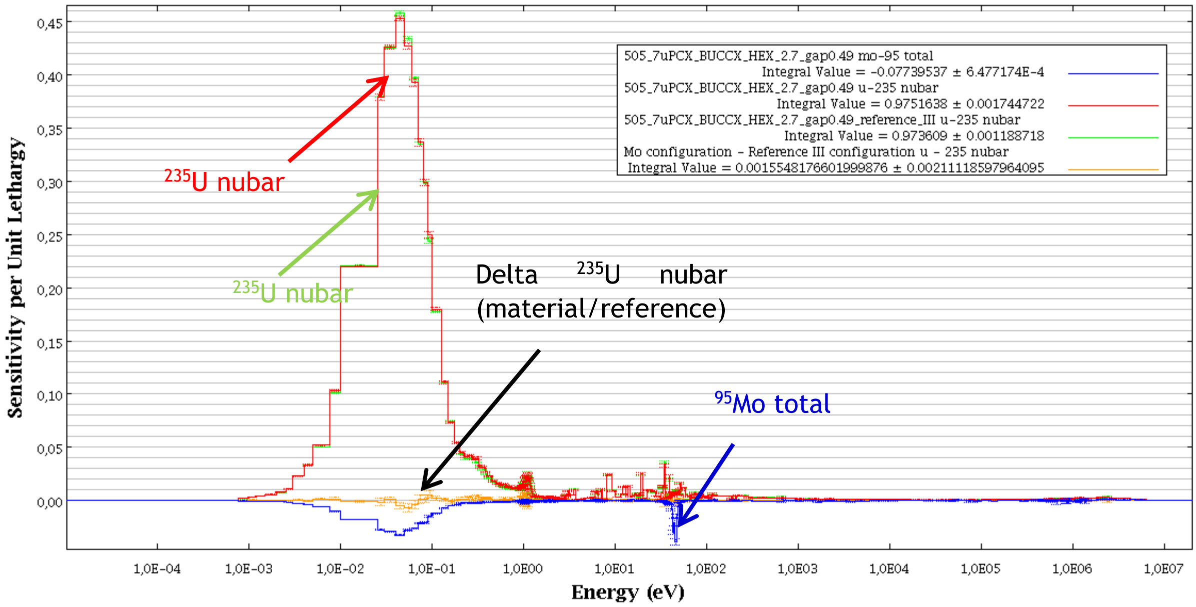

Figure 27. Sensitivity Profile of ^{95}Mo total cross section compared with difference of sensitivity for ^{235}U nubar, between **505_7uPCX_216_BUCCX_hex_2.7** *experiment with molybdenum and its reference III*

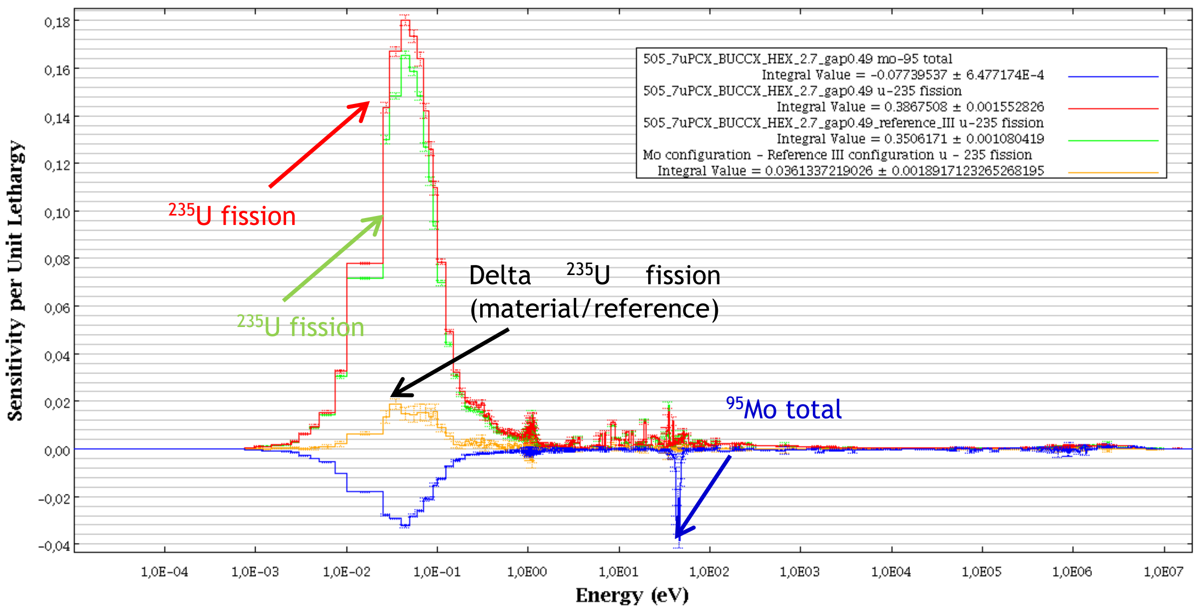

Figure 28. Sensitivity Profile of ^{95}Mo total cross section compared with difference of sensitivity for ^{235}U fission, between **505_7uPCX_216_BUCCX_hex_2.7** *experiment with molybdenum and its reference III*

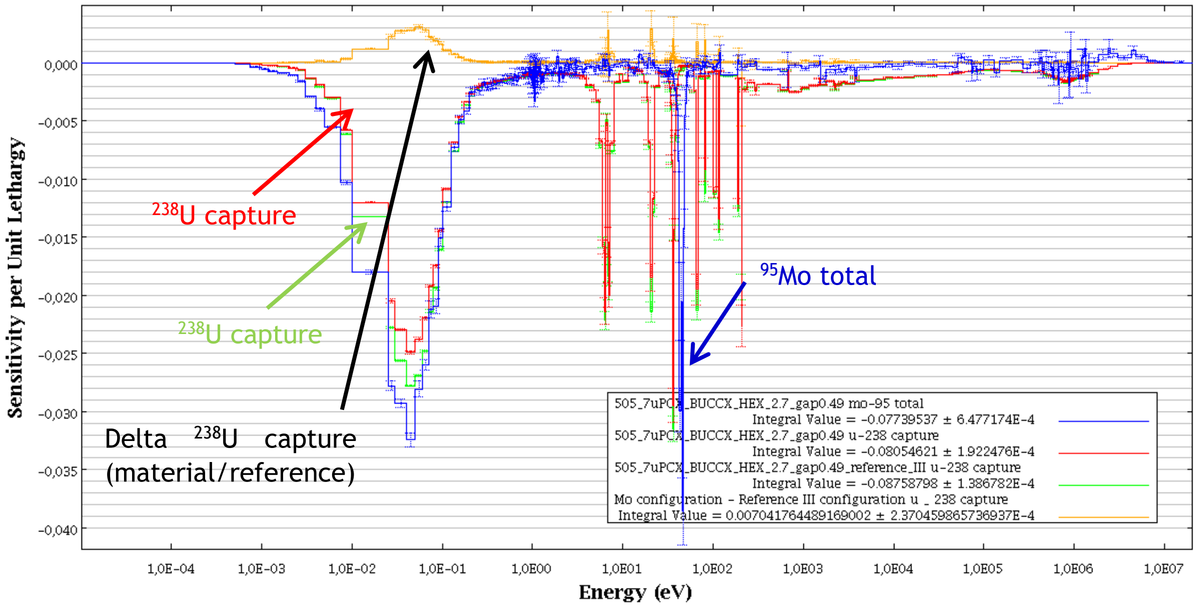

Figure 29. Sensitivity Profile of ^{95}Mo total cross section compared with difference of sensitivity for ^{238}U capture, between **505_7uPCX_216_BUCCX_hex_2.7** *experiment with molybdenum and its reference III*

It should be noted that no comparison with the **7uPCX_547sleeves_th0.03_1039rods_p1.6 configuration is presented in this report. However, it was checked that the reference experiments selected previously agreed with the new configuration.**

4 EVALUATION OF EXPERIMENTAL UNCERTAINTIES

Part of the work to be done in a CED-2 report consists in propagating the uncertainties in terms of Δk_{eff}. This step is paramount to establish tolerance values for the manufacturing of molybdenum sleeves or foils and to ensure that the overall uncertainty is not driven by the uncertainty on molybdenum materials.

It can be concluded from previous LCT-078, LCT-079 and LCT-096 evaluations that the main components of the overall uncertainty should be the uncertainties pertaining to the pitch between rods, the clad outer diameter and the thickness of molybdenum sleeves/foils/rods.

The same 1σ uncertainties for the parameters relating to the BUCCX and 7uPCX rods as in LCT-079 and LCT-096 were retained [4].

Concerning the thickness of molybdenum foils, the uncertainty was fixed at 0.001 cm as in LCT-079.

Concerning the density of molybdenum foils and sleeves, the uncertainty was fixed at 0.01 g/cm^3

Concerning the thickness of molybdenum sleeves, the uncertainty of 0.000282 cm of the titanium sleeves encountered in LEU-COMP-THERM-099 evaluation was retained.

Measurements of the sleeves should contribute to an improvement of the uncertainty assessment.

To perform the experiments, new grids will need to be fabricated to adapt the pitches. In a first step, it is proposed for configurations with BUCCX rods to keep the same grid hole diameters and therefore the same value of gap grid hole/rod (0.020955 cm). For configurations with 7uPCX rods, as sleeves are wrapped around the rods, the grid holes need to be larger. The same gap grid hole/rod as in other experiments involving 7uPCX rods is kept (0.01602 cm), which fixes the new dimension of grid holes.

It is to be noted that all uncertainties are assumed to be 100% systematic as it is the case in Sandia LEU-COMP-THERM-079 and LEU-COMP-THERM-096 benchmarks.

Concerning the rod positioning uncertainty, the “traditional” method applied up to now in the evaluation of experiments consists in making a k_{eff} calculation increasing the pitch (spacing between rods) by a given value, then making another Monte Carlo calculation decreasing it of the same value, and then making the difference of the two calculations. This method is known to overestimate the uncertainty of the rod position. In fact, it does not account for the constraint that the grid represents. Indeed, the position of the rods is conditioned by the fact that the rods are maintained by grids and that the gap between the grid and the rod has a given value. A Monte Carlo random sampling methodology would be needed to determine the exact uncertainty. It was not performed for this report and shall be done in the final ICSBEP evaluation.

The uncertainties were propagated in terms of Δk_{eff} using the MORET 5.C.1 Monte Carlo code with the JEFF-3.1.1 nuclear data evaluation. Uncertainties pertaining to chemistry were propagated using the correlated sampling method (CS) [8]. Uncertainties pertaining to the geometry were propagated through direct perturbation calculations (DC) with a low Monte Carlo standard deviation (typically 0.00010). The results for the three studied configurations are reported in Table 13, Table 14 and in Table 16.

Table 13: Propagation of 1σ uncertainties for 18x18_144.

Parameter	1σ uncertainty (systematic)	Variation	(k_{eff}(+variation)-k_{eff}(-variation))/2	Scaling factor	Method	Δk_{eff} (1σ)
Uranium Isotopic Content ^{235}U (at.%)	0.013%	0.013%	58	1	CS	58
Rod Fuel UO_2 Mass (g)	±0.25 g	±0.25 g	28	1	DC	28
Fuel Rod position (cm)	0.0016	0.002867	160	0.0016/0.002867	DC	89
Fuel pellet diameter measurement (cm)	0.0025	0.0025	23	1	DC	23
Uranium Mass Fraction (%) (stoichiometry)	0.00261	0.00261	7	1	CS	7
Temperature (°C)	1	1	2	1	DC	2
Clad outer diameter (cm)	0.000106	0.00293	126	0.000106/0.00293	DC	5
Clad inner diameter (cm)	0.00293	0.00293	16	1	DC	16
Fuel Clad Composition	100%	100%	1	1	DC	Negligible
Foils diameter (cm) - keeping mass constant	0.0044	0.0044	8	1	CS	8
Foils thickness (cm) - keeping mass constant	0.001	0.001	5	1	DC	5
Foils density (g/cm^3)	0.01/√3	0.01	Negligible	1/√3	EC	Negligible
TOTAL						**114**

Table 14: Propagation of 1σ uncertainties for 7uPCX_547sleeves_18crowns.

Parameter	1σ uncertainty (systematic)	Variation	(k_{eff}(+variation)-k_{eff}(-variation))/2	Scaling factor	Method	Δk_{eff} (1σ)
Uranium Isotopic Content ^{235}U (at.%)	0.0071	0.0071	26	1	CS	26
Rod Fuel UO_2 Mass (g)	0.02	0.02	4	1	DC	4
Fuel Rod position (cm)	0.00094	0.00094	Negligible	1	DC	Negligible
Fuel detected Impurities	50%/√3	50%	10	1/√3	CS	6
Fuel impurities below the detection limit	100%/√3	100%	3	1/√3	CS	2
Fuel pellet diameter measurement (cm)	0.000072	0.000072	6	1	DC	6
O/U stoichiometry	0.1/√3	0.1	55	1/√3	CS	32
Temperature (°C)	1/√3	1	6	1/√3	DC	3
Clad outer diameter (cm)	0.0000954	0.0000954	12	1	DC	12
Clad inner diameter (cm)	0.000164	0.000164	8	1	DC	8
^{234}U (%)	0.00013	0.00013	Negligible	1	CS	Negligible
^{236}U (%)	0.00063	0.00063	1	1	CS	1
Fuel Clad Composition	100%/√3	100%	17	1/√3	DC	10
Sleeves Thickness (cm) - keeping mass constant	0.000282	0.001	164	0.000282/0.001	DC	46
Sleeves density (g/cm^3)	0.01/√3	0.05	58	(0.01/0.05)/√3	EC	7
Gap sleeve/rod (cm)	0.0002	0.002	131	1	DC	13
TOTAL						**67**

Table 15: Propagation of 1σ uncertainties for 7uPCX_547sleeves_th0.03_1039rods_p1.6.

Parameter	1σ uncertainty (systematic)	Variation	(k_{eff}(+variation)-k_{eff}(-variation))/2	Scaling factor	Method	Δk_{eff} (1σ)
Uranium Isotopic Content ^{235}U (at.%)	0.0071	0.0071	30	1	CS	30
Rod Fuel UO_2 Mass (g)	0.02	0.02	4	1	DC	4
Fuel Rod position (cm)	0.00075	0.0013	19	0.00075/0.0013	DC	11
Fuel detected Impurities	50%/√3	50%	10	1/√3	CS	6
Fuel impurities below the detection limit	100%/√3	100%	3	1/√3	CS	2
Fuel pellet diameter measurement (cm)	0.000072	0.000072	6	1	DC	6
O/U stoichiometry	0.1/√3	0.1	45	1/√3	CS	26
Temperature (°C)	1/√3	1	17	1/√3	DC	10
Clad outer diameter (cm)	0.0000954	0.0000954	8	1	DC	8
Clad inner diameter (cm)	0.000164	0.000164	2	1	DC	2
^{234}U (%)	0.00013	0.00013	Negligible	1	CS	Negligible
^{236}U (%)	0.00063	0.00063	Negligible	1	CS	Negligible
Fuel Clad Composition	100%/√3	100%	18	1/√3	DC	10
Sleeves Thickness (cm) - keeping mass constant	0.00762/√3 (1)	0.00762	997	1/√3	DC	576
	0.000762/√3 (2)					58
Sleeves density (g/cm^3)	0.01/√3	0.01	12	1/√3	EC	7
Gap sleeve/rod (cm)	0.0002	0.002	362	0.0002/0.002	DC	36
TOTAL (1)						**579**
TOTAL (2)						**82**

Table 16: Propagation of 1σ uncertainties for 505_7uPCX_216_BUCCX_hex_2.7.

Parameter	1σ uncertainty (systematic)	Variation	(k_{eff}(+variation)-k_{eff}(-variation))/2	Scaling factor	Method	Δk_{eff} (1σ)
Uranium Isotopic Content ${}^{235}U$ (at.%) - 7uPCX	0.0071	0.0071	11	1	CS	11
Uranium Isotopic Content ${}^{235}U$ (at.%) - BUCCX	0.013	0.013	53	1	CS	53
Rod Fuel UO_2 Mass (g) - 7uPCX	0.02	0.02	2	1	DC	2
Rod Fuel UO_2 Mass (g) - BUCCX	0.25	0.25	5	1	DC	5
Fuel Rod position (cm)	0.00094	0.00094	8	1	DC	8
Fuel detected Impurities	50%/√3	50%	12	1/√3	CS	7
Fuel impurities below the detection limit	100%/√3	100%	1	1/√3	CS	1
Fuel pellet diameter measurement (cm) 7uPCX	0.000072	0.000072	14	1	DC	14
Fuel pellet diameter measurement (cm) BUCCX	0.0025	0.0025	4	1	DC	4
O/U stoichiometry 7uPCX	0.1	0.1	48	1/√3	CS	28
Uranium Mass Fraction (%) (stoichiometry) BUCXX	0.00261	0.00261	81	1	CS	81
Temperature (°C)	1/√3	1	2	1/√3	DC	1

Parameter	1σ uncertainty (systematic)	Variation	(k_{eff}(+variation)-k_{eff}(-variation))/2	Scaling factor	Method	Δk_{eff} (1σ)
Clad outer BUCCX diameter (cm)	0.000106	0.00293	20	0.000106/0.00293	DC	1
Clad inner BUCCX diameter (cm)	0.00293	0.00293	2	1	DC	2
Clad outer 7uPCX diameter (cm)	0.0000954	0.0000954	2	1	DC	Negligible
Clad inner 7uPCX diameter (cm)	0.000164	0.000164	4	1	DC	4
^{234}U (%)	0.00013	0.00013	Negligible	1	CS	Negligible
^{236}U (%)	0.00063	0.00063	Negligible	1	CS	Negligible
Fuel Clad Composition (BUCCX rods)	100%/√3	100%	9	1/√3	DC	5
Fuel Clad Composition (7uPCX rods)	100%/√3	100%	20	1/√3	DC	12
Sleeves Thickness (cm) - keeping mass constant	0.000282/√3	0.001	9	1/√3	DC	Negligible
Sleeves density (g/cm^3)	0.01/√3	0.05	50	(0.01/0.05)/√3	EC	6
TOTAL						**104**

One can see that, for the design involving molybdenum and molybdenum foils, the uncertainty due to the BUCCX rods is dominant. As a consequence, a design with 7uPCX rods and molybdenum sleeves would decrease the overall uncertainty provided that stringent tolerances on molybdenum thickness could be respected.

5 FEASIBILITY STUDY

Another step of the CED-2 report consists in ensuring that the experiments are feasible and, in particular that the molybdenum foils or sleeves can be fabricated with the given tolerances. Through a review in the literature[a], it has been established that foils having a thickness comprised between 0.125 mm and 12.7 mm could be fabricated. In our case, the optimum integral sensitivity to the capture of ^{95}Mo is obtained for a thickness comprised between 4 and 7 mm. This thickness is well bound by the tolerance values of the suppliers.

A similar study was performed for the molybdenum sleeves. It was found that manufacturers could fabricate sleeves with a diameter comprised between 0.0508 cm and 15.24 cm and a thickness comprised between 0.00762 cm and 1.27 cm. For our optimized case, the thickness of sleeves is set around 0.1 cm and 0.13 cm. It is therefore bound by the fabrication tolerances.

Moreover, the gap between the rods and the sleeves was chosen as being 0.025 cm. This is the value that was retained for the MIRTE experiments involving slightly larger and less precise rods. This should be feasible with more precise rods as it is the case with the 7uPCX rods.

Concerning the costs of the material to be fabricated, an estimate has been established by the PLANSEE company at the end of 2016. The fabrication cost to surround 7UPCX rods for the 547 sleeves encountered in the 7uPCX-547sleeves-18crowns experiment is comprised between 200,000 € and 300,000 € in a first estimate, depending of the tolerance values imposed for the sleeves dimensions.

Concerning molybdenum sleeves surrounding BUCCX rods, an estimate was asked to the same supplier and it seems that, for a total of 216 sleeves, the cost would be slightly higher taking into account the sleeves dimensions.

6 DEFINITION OF EXPERIMENTS

6.1 Two types of critical approaches

The configurations defined in the CED-1 report were optimal with regards to the integral sensitivity to the capture of ^{95}Mo. A margin of over-criticality was retained so that the experiments could be done even if nuclear data over estimate k_{eff}. However, this margin was sometimes too large. It is therefore proposed to re-optimize the configurations and to calculate k_{eff} versus varying parameter using the two types of critical approaches (rod number and water critical height). It will then be possible to interpolate k_{eff}.

Calculations were performed with the continuous energy MORET 5.D.1 using the ENDF/B-VII.0 library. The standard deviation of the Monte Carlo was fixed at 0.00030.

The results are given in Table 17 through Table 20 for configurations with the material of interest and from Table 21 to Table 23 for reference experiments.

[a] https://www.americanelements.com/molybdenum-sleeve-7439-98-7
http://www.goodfellow.com/catalogue/GFCat4B.php?ewd_token=OiwpbH3SaUnULPgLflPfRpzeIL7OrN&n=lHzksXqB0ZF7fnspBrN5Xc1Kr5Rix1

Table 17: Two types of sub-critical approaches for 18x18_144.

Approach by increase of water level		**Approach "fully reflected" with addition of fissile rods**	
Critical height of water (cm) from bottom of fuel column	**k_{eff}**	**Number of rods**	**k_{eff}**
10	0.59062	256 (16 × 16)	0.96629
12	0.65424	272 (16 × 17)	0.98053
14	0.70737	289 (17 × 17)	0.99351
16	0.75130	306 (18 × 17)	1.00083
18	0.78877	324 (18 × 18)	1.0122
20	0.82066		
22	0.84835		
24	0.87197		
26	0.89155		
28	0.90925		
30	0.92558		
32	0.93853		
34	0.95085		
36	0.96113		
38	0.97014		
40	0.97863		
42	0.98603		
44	0.99240		
46	0.99884		
48	1.00397		
48.78	1.00518		

Table 18: Two types of sub-critical approaches for 7uPCX_547sleeves_18crowns.

Approach by increase of water level		**Approach "fully reflected" with addition of fissile rods**	
Critical height of water (cm) from bottom of fuel column	**k_{eff}**	**Number of rods (crowns)**	**k_{eff}**
10	0.64701	631 (15)	0.90455
12	0.70349	721 (16)	0.93446
14	0.73647	817 (17)	0.96319
16	0.77201	919 (18)	0.98833
18	0.80284	1027 (19)	1.01687
20	0.82966		
22	0.85141		
24	0.87153		
26	0.88919		
28	0.90438		
30	0.91688		
32	0.92889		
34	0.93966		
36	0.94870		
38	0.95715		
40	0.96340		
42	0.97015		
44	0.97640		
46	0.98232		
48	0.98560		
49	0.98744		
50	0.98909*		

* To reach criticality, it will be necessary to add rods at the periphery of the driver lattice

Table 19: Two types of sub-critical approaches for 7uPCX_547sleeves_th0.03_20crowns_p1.6.

Approach by increase of water level		**Approach "fully reflected" with addition of fissile rods**	
Critical height of water (cm) from bottom of fuel column	**k_{eff}**	**Number of rods (crowns)**	**k_{eff}**
4.878	0.52872 (30)	817 (17)	0.94727 (23)
9.756	0.71640 (30)	919 (18)	0.97482 (23)
14.634	0.84168 (30)	1027 (19)	1.00171 (30)
19.512	0.91749 (30)	1141 (20)	1.02708 (97)
24.39	0.96537 (30)		
29.268	0.99680 (30)		
34.146	1.01893 (30)		
39.024	1.02413 (30)		

Table 20: Two types of sub-critical approaches for 505_7uPCX_216_BUCCX_hex_2.7.

Approach by increase of water level		*Approach "fully reflected" with addition of fissile rods*		
Critical height of water (cm) from bottom of fuel column	**k_{eff}**	**Number of 7uPCX rods**	**Number of BUCCX sleeved rods**	**k_{eff}**
0	0.13210	181	216	0.97000
5	0.34075	253	216	0.97995
10	0.56973	331	216	0.99106
15	0.71585	415	216	0.99984
20	0.80945	505	216	1.00566
25	0.87212			
30	0.91561			
35	0.94797			
40	0.97037			
45	0.98795			
50	1.00135			
51	1.00210			
52	1.00285			
53	1.00306			
54	1.00429			
55	1.00394			
56	1.00547			
57	1.00614			
58	1.00571			
59	1.00567			
60	1.00632			
61	1.00588			

Table 21: Two types of sub-critical approaches for Ref-18x18_144.

Approach by increase of water level		**Approach "fully reflected" with addition of fissile rods**	
Critical height of water (cm) from bottom of fuel column	**k_{eff}**	**Number of rods**	**k_{eff}**
6	0.44161	169 (13 × 13)	0.90900
8	0.53823	196 (14 × 14)	0.93821
10	0.61908	225 (15 × 15)	0.97902
12	0.68732	256 (16 × 16)	1.00305
14	0.74335	289 (17 × 17)	1.02390
16	0.78965		
18	0.82927		
20	0.86302		
22	0.89146		
24	0.91552		
26	0.93689		
28	0.95530		
30	0.97028		
32	0.98360		
34	0.99536		
36	1.00519		
38	1.01336		

Table 22: Two types of sub-critical approaches for Ref-7uPCX_547sleeves_18crowns.

Approach by increase of water level		**Approach "fully reflected" with addition of fissile rods**	
Critical height of water (cm) from bottom of fuel column	**k_{eff}**	**Number of rods (crowns)**	**k_{eff}**
10	0.62578	331 (11)	0.99119
12	0.70800	397 (12)	1.03062
14	0.77534	469 (13)	1.06594
16	0.83083		
18	0.87732		
20	0.91692		
22	0.94930		
24	0.97821		
26	1.00200		
28	1.02341		

Table 23: Sub-critical approaches for Ref-505_7uPCX_216_BUCCX_hex_2.7.

Approach by increase of water level (Ref3-505_7uPCX_216_BUCCX_hex_2.7)	
Critical height of water (cm) from bottom of fuel column	k_{eff}
0	0.10438
5	0.30709
10	0.55018
15	0.71933
20	0.81350
25	0.88259
30	0.92875
35	0.96562
40	0.98964
41	0.99354
42	0.99838
43	1.00048
44	1.00497
45	1.00715
46	1.01212
47	1.01526
48	1.01664
49	1.02013
50	1.02293
55	1.02872
60	1.02840

We can see that the two types of critical approaches can be performed in SPRF/CX facility. However, the “fully reflected” approach would require irregular lattices of rods with additional rods on the periphery.

6.2 Calculations with various libraries

In order to identify possible biases due to nuclear data for the three main configurations, calculations were performed with the MORET 5.D.1 continuous energy code using various nuclear data libraries. The differences of k_{eff} between the ENDF/B-VII.0 evaluation and other evaluations are presented in Table 24. Only the configurations in “fully reflected” critical approach are considered in this section.

Table 24 : Results with various codes and libraries (σ_{MC} < 0.00030). Discrepancies are given in pcm.

Configuration	Pitch (cm)	Difference JEFF-3.1.1-ENDFB-VII.0	Difference JEFF-3.2-ENDFB-VII.0	Difference ENDF/B-VII.1-ENDFB-VII.0
18 x 18_144	2.018	-64	-3	34
7uPCX_547sleeves_18crowns	1.566	134	86	93
7uPCX_547sleeves_th0.03_1039rods_p1.6	1.6	168	103	164
505_7uPCX_216_BUCCX_hex_2.7	2.7	-6	-80	109
Ref-18 x 18_144	2.018	-98	-115	-119
Ref-7uPCX_547sleeves_18crowns	1.566	27	93	9
Ref1-505_7uPCX_216_BUCCX_hex_2.93	2.93	-141	-185	16
Ref2-505_7uPCX_216_BUCCX_hex_2.7	2.7	-105	-143	4
Ref3-505_7uPCX_216_BUCCX_hex_2.93	2.7	-103	-146	-14

The first observation is that even if various nuclear data libraries are used, the k_{eff} differences remain quite low, even if they are sometimes significant when compared with the Monte Carlo standard deviations.

In a second step, it is proposed to check the influence of the molybdenum cross sections only. The JEFF-3.1.1 evaluation is used for all elements, except for ^{95}Mo for which various evaluations are used. The differences in k_{eff} between the JEFF-3.1.1 and other evaluations of nuclear data are reported in Table 25.

Table 25 : Results with various libraries for ^{95}Mo (σ_{MC} < 0.00030). Discrepancies are given in pcm.

Configuration	Pitch (cm)	MORET 5.D.1		
		Difference JEFF-3.2-JEFF-3.1.1	Difference ENDF/B-VII.0-JEFF-3.1.1	Difference ENDF/B-VII.1-JEFF-3.1.1
18 x 18_144	2.018	75	80	162
7uPCX_547sleeves_18crowns	1.566	68	-57	166
7uPCX_547sleeves_th0.03_1039rods_p1.6	1.6	25	5	233
505_7uPCX_216_BUCCX_hex_2.7	2.7	12	-15	151

It can be concluded that, for molybdenum, the JEFF-3.2, ENDF/B-VII.0 and JEFF-3.1.1 evaluations are perfectly consistent in thermal energy range. Some differences exist with the ENDF/B-VII.1 library (see Figure 30) and other libraries in the thermal energy range. Differences can also be pointed out between JEFF-3.1.1 and other libraries in the unresolved resonances energy range.

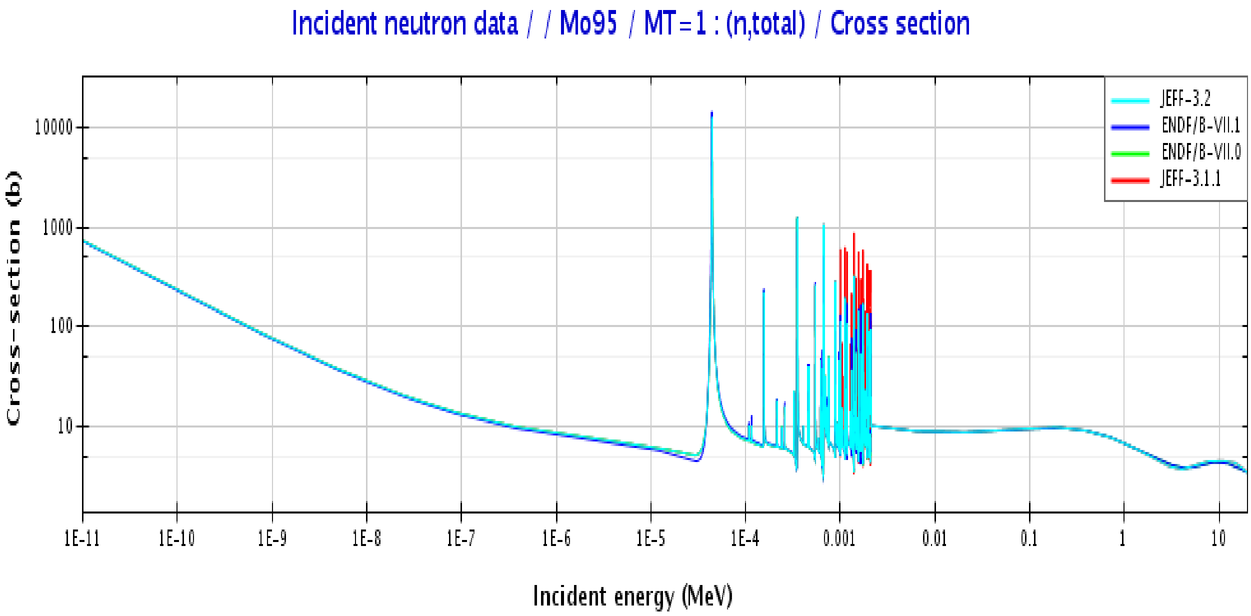

Figure 30. Cross section of ^{95}Mo for different evaluations.

6.3 Spectral indices

Models of the configurations were prepared in continuous energy KENO-V.a from SCALE 6.1.

3-energy-group fission rates tallies from the SCALE 6.1 (continuous energy KENO-V.a with ENDF/VII.0 evaluation for nuclear data) package are reported in Table 26.

Mo capture rates calculated with MORET 5.D.1 are reported in Table 27.

Even if the majority of fissions occur in the thermal energy range, part of them occurs in the epithermal energy range and their proportion varies slightly from one configuration to another.

Table 26: Fission rates in 3-energy groups for the optimized configurations.

Configuration	Group 3 (< 0.625 eV)	Group 2 (0.625 eV < E < 100 keV)	Group 1 (> 100 keV)
18 x 18_144	0.8564	0.0886	0.0550
7uPCX_547sleeves_18crowns	0.8309	0.1392	0.0299
7uPCX_547sleeves_th0.03_1039rods_p1.6	0.9225	0.0553	0.0222
505_7uPCX_216_BUCCX_hex_2.7	0.8564	0.1107	0.0329

Table 27: Mo capture reaction rate in 3-energy groups for the optimized configurations.

Configuration	Group 3 (< 0.625 eV)	Group 2 (0.625 eV < E < 100 keV)	Group 1 (> 100 keV)
18 x 18_144	0.7022	0.2843	0.0135
7uPCX_547sleeves_18crowns	0.7768	0.2152	0.0079
7uPCX_547sleeves_th0.03_1039rods_p1.6	0.7719	0.2215	0.0066
505_7uPCX_216_BUCCX_hex_2.7	0.8339	0.1615	0.0047

6.4 Calculation of βeff

The β_{eff} is an important parameter to estimate the reactivity of a nuclear system. The values of this parameter calculated with the MORET 5.D.1 code are provided in Table 28.

Table 28: β_{eff} for the three main configurations with ENDF/B-VII.0 evaluation.

Configuration	β_{eff} in pcm	1σ uncertainty in pcm
18 x 18_144	755	3.9
7uPCX_547sleeves_18crowns	735	4.9
7uPCX_547sleeves_th0.03_1039rods_p1.6	720	3.2
505_7uPCX_216_BUCCX_hex_2.7	708	3.4
Ref-18 x 18_144	773	4.5
Ref-7uPCX_547sleeves_18crowns	774	4.6
Ref1-505_7uPCX_150_BUCCX_hex_2.93	730	3.6
Ref2-505_7uPCX_117_BUCCX_hex_2.7	741	3.6
Ref3-505_7uPCX_144_BUCCX_hex_2.7	747	3.6

6.5 Definition of experiments grid

Many designs have been tested in this report involving either BUCCX rods of 7uPCX rods in lattices. It appears that only experiments involving rods surrounded by molybdenum sleeves allow exhibiting sensitivities of k_{eff} to ^{95}Mo total cross section significantly higher than for previous experiments.

Regarding experiments involving Molybdenum sleeves, two designs were tested: one with a test zone involving molybdenum sleeves around 7uPCX rods and another with a test zone involving molybdenum sleeves around BUCCX rods. First estimations highlight that the cost of molybdenum sleeves dedicated to BUCCX rods should be slightly higher than the cost of sleeves for 7uPCX rods and they should lead to an integral sensitivity of k_{eff} to the total cross section of ^{95}Mo slightly lower. Therefore, experiments involving 7uPCX rods sleeved by Molybdenum seems to be the best compromise, even if the use of BUCCX rods would allow using the grids employed in the design of LEU-COMP-THERM-099 experiments already performed at SNL.

Moreover, if the cost analysis shows that the design with molybdenum sleeves around 7uPCX rods is too expensive, it is still possible to limit the number of rods surrounded by sleeves while keeping an acceptable sensitivity of k_{eff} to the total cross section of ^{95}Mo.

Experiments that could be performed at Sandia include:

- repeatability experiments (Rv) which consist in redoing the critical approach after water draining;
- reproducibility experiments, which consist in sampling the position of the rods within the lattice and then redo the critical approach
- reference experiments allowing feedback on nuclear data when compared with the experiment with material. It is envisioned to do the critical approach increasing the water level; however, for the experiment with molybdenum it would be appreciated to perform a critical approach with the “fully reflected” configuration.

Thus, at least 6 critical experiments could be performed: the **7uPCX_547sleeves_th0.03_1039rods_p1.6 with the two criticality approaches (water level increase and “fully reflected”), one repeatability experiment for the water level increase experiment, a reference experiment without molybdenum sleeves and its associated repeatability experiment and an experiment where the position of rods is sampled inside the lattice. However, the wall thickness of sleeves must be known with a high precision otherwise large uncertainties will be obtained. It results in strong constraints on their manufacturing.**

The main characteristics of the configuration involving 7uPCX rods and Mo sleeves are reminded in Table 29.

Table 29: Main characteristics of configuration involving Mo sleeves.

Parameter	Value
Sleeves Thickness (cm)	0.0762
Sleeves height (cm)	69.5452
Sleeves internal radius (cm)	0.5588
Sleeves external radius (cm)	0.635
7uPCX rods clad radius (cm)	0.317474
7uPCX rods pellet radius (cm)	0.262814
Pitch between rods (cm)	1.6
Number of 7uPCX rods with sleeves	547
Total number of 7uPCX rods	1039

7 COMPLIANCE WITH C_EDT MANUAL REQUIREMENTS

The C_EdT manual [9] provides an example of required input and calculated values for design, execution and documentation of criticality (k_{eff}) measurement experiments.

Table 30 replicates the columns of the table applicable to the current CED-2 status for IER-305. Also shown in the table is a brief response for this IER.

Table 30: C_EdT Manual Example Requirements for CED-2 of a Criticality Measurement Experiment. The first and second columns are replicated from Table 5.1 of the manual.

Input Parameters	**Design CED-2**
Compositions (N)	See LCT-096 for 7uPCX rods and LCT-078 for BUCCX rods and Appendix
Dimensions (x)	See LCT-096 for 7uPCX rods and LCT-078 for BUCCX rods and Appendix
Positions (y, σ_y)	✓
Sleeves specifications	✓
Budget for procurement of sleeves	✓
Input file	✓
Draft of section 1 and 2 of ICSBEP	✓
Calculated parameters	**Design CED-2**
Eigenvalue (k_{eff}, σ_k)	✓
Material worth (Δk_{eff}, $\sigma_{\Delta k}$)	✓
Neutron balance	✓
Flux	-
Isotope Sensitivities (by Reaction)	✓
Match between proposed experiment and application case	✓

8 CONCLUSIONS

This report is the continuation of the CED-1 report [2] since it improves the design of the proposed experiments, adding new ones with molybdenum sleeves surrounding BUCCX rods. It also proposes reference experiments without molybdenum in order to optimize the feedback on nuclear data.

Moreover, it gives the k_{eff} evolution versus critical parameter of interest for two types of critical approaches:

- Water level increase,
- Or “fully reflected” approach by addition of rods.

Three configurations were tested: one involving Molybdenum foils and two involving Mo sleeves surrounding either 7UPCX or BUCCX rods.

Experiments involving BUCCX foils were discarded due to the low increase of sensitivities of k_{eff} to the cross sections of ^{95}Mo when compared to existing experiments.

The design involving Mo sleeves is privileged since it leads to higher sensitivities of k_{eff} to the total cross section of ^{95}Mo and offers the opportunity to improve sensitivity of k_{eff} to the cross sections of ^{95}Mo when compared with former experiments. As it shows higher sensitivities to Mo cross section and leads to lower fabrication costs, the configuration with 7uPCX rods is preferred.

All in all, at least 6 experiments are proposed including reference experiments and the repeatability ones.

A first estimate of the cost of the supply and manufacturing of molybdenum sleeves has been done. Using 547 sleeves, the total cost should amount to about 200,000 €-300,000 €, depending on the fabrication tolerances. Of course, it is a first estimate that would need to be refined and a reduction of the number of sleeved-rods is still possible keeping a satisfying sensitivity to Mo cross section.

APPENDIX

Composition of UO_2 BUCCX rods

The same composition as for LCT-079 is retained and is provided in the table below.

Table 31: Composition of BUCCX fuel.

Element	**Concentration [Atom/barn-cm]**
^{234}U	5.1985E-06
^{235}U	1.0132E-03
^{236}U	5.1544E-06
^{238}U	2.2221E-02
O	4.6888E-02

Composition of UO_2 7uPCX rods

The same composition as for LCT-096 is retained and is provided in the table below; except that impurities have been removed.

Table 32: Composition of 7uPCX fuel.

Element	**Concentration [Atom/barn-cm]**
^{234}U	6.5539E-06
^{235}U	1.6010E-03
^{236}U	1.4632E-06
^{238}U	2.1296E-02
O	4.5837E-02

Composition of molybdenum sleeves and foils

Molybdenum is assumed to be natural; its density is taken as 10.222 g/cm^3. The composition of molybdenum is given in the table below.

Table 33: Composition of Mo.

Element	**Concentration [Atom/barn-cm]**
Mo	6.4150E-02

<u>Geometry of configuration with 7uPCX rods and molybdenum sleeves – 7uPCX_547sleeves_18crowns</u>

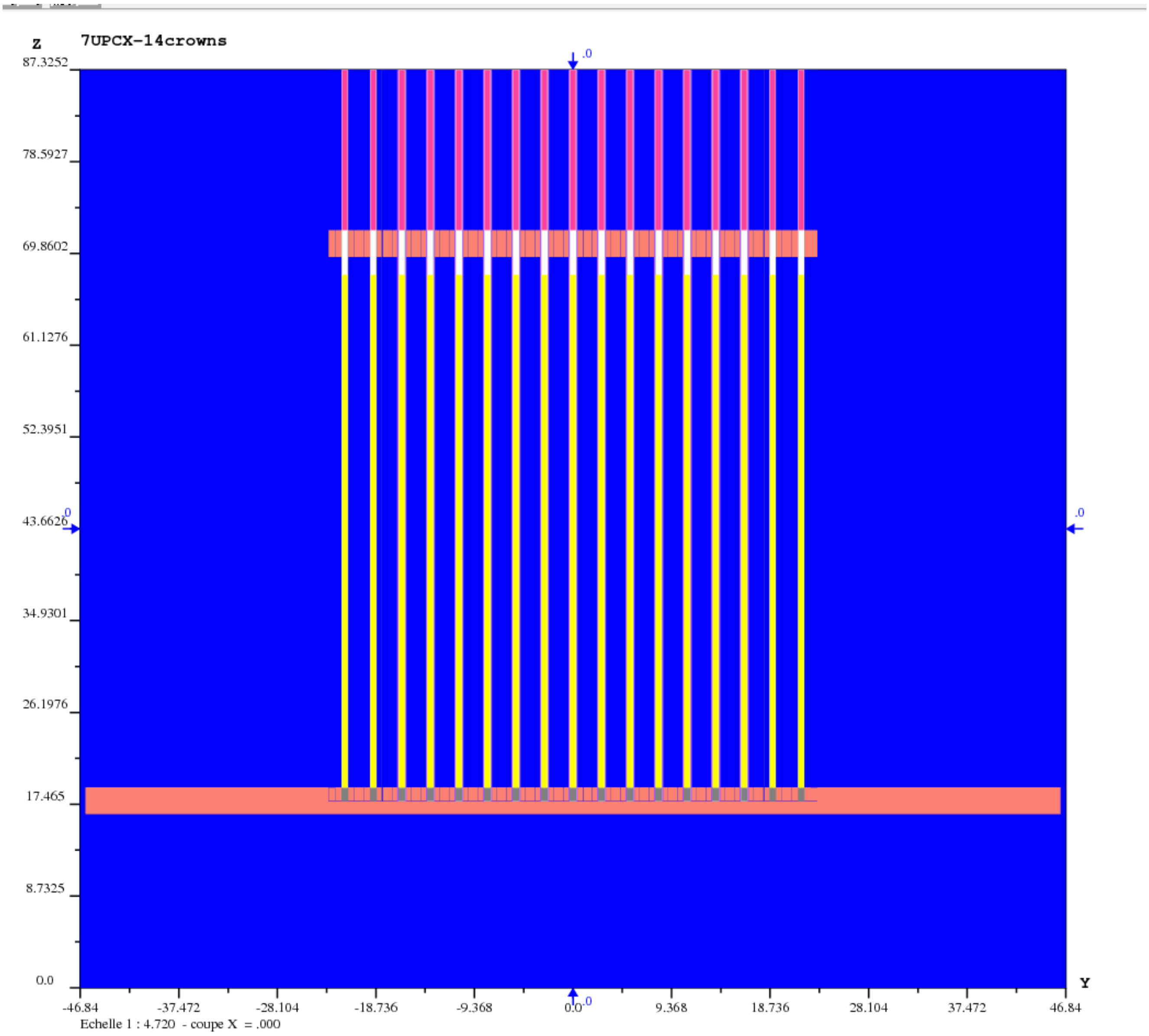

Figure 31. Vertical cross cut view of configuration with 7uPCX rods and Mo sleeves – 7uPCX_547sleeves_18crowns.

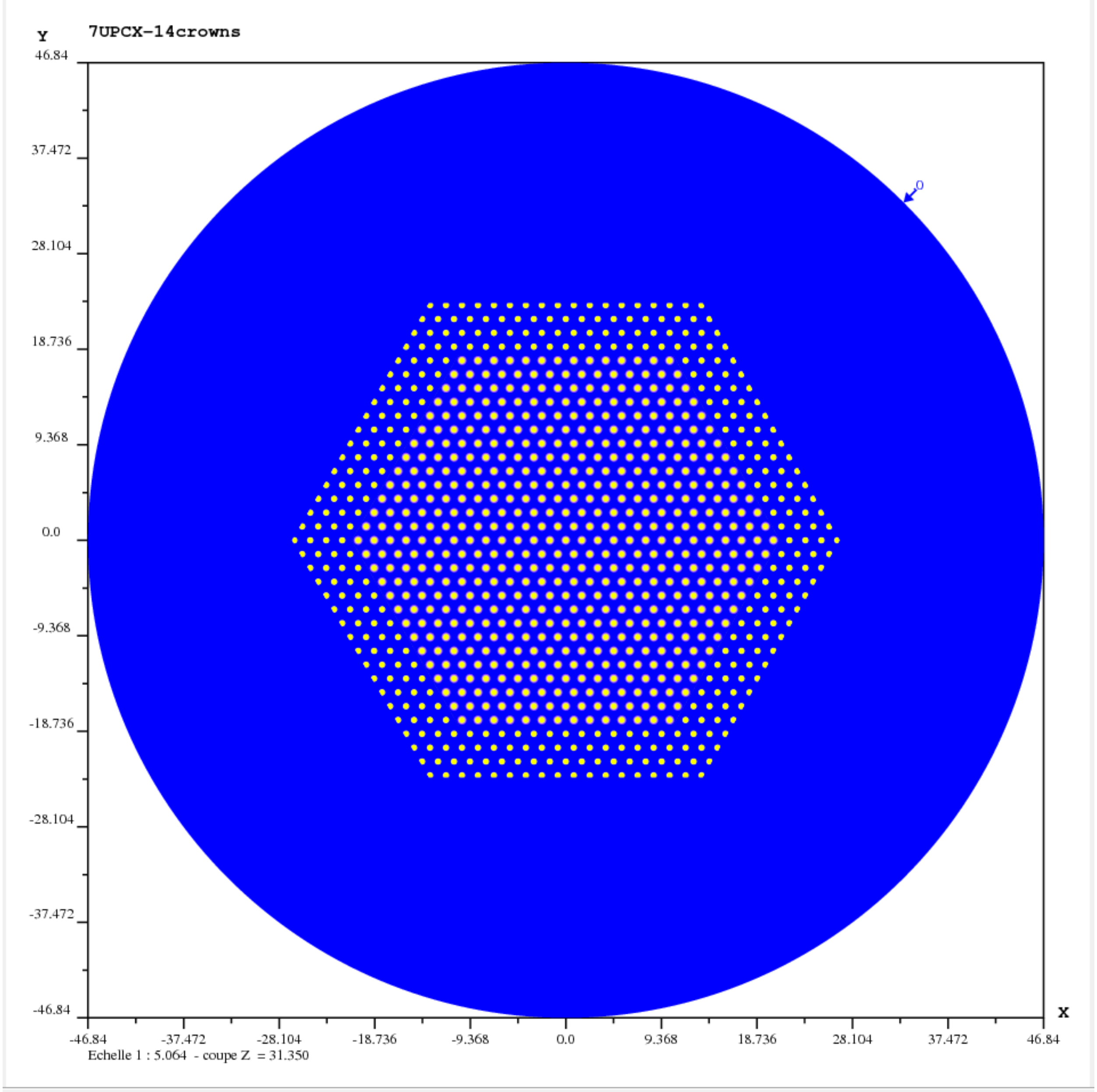

Figure 32. Horizontal cross cut view of configuration with 7uPCX rods and Mo sleeves - 7uPCX_547sleeves_18crowns.

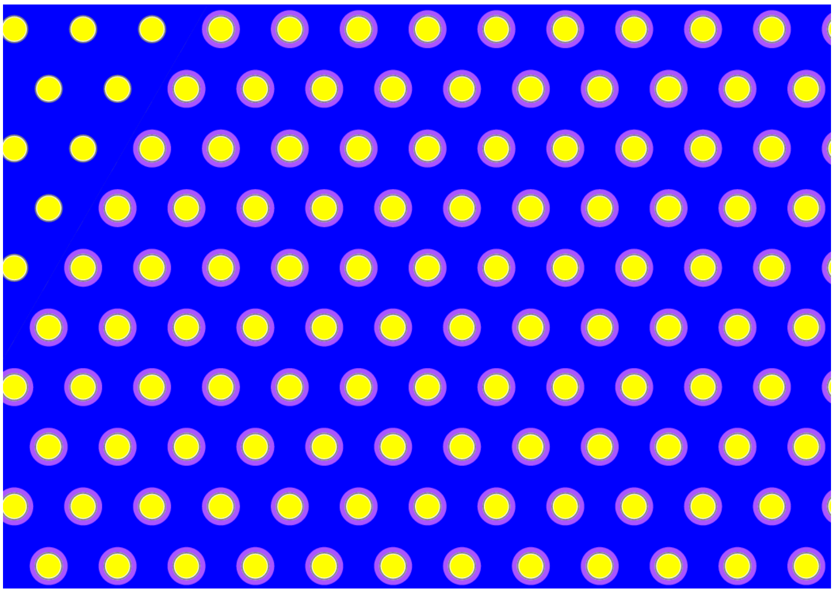

Figure 33. Horizontal cross cut view of configuration with 7uPCX rods and Mo sleeves - zoom - 7uPCX_547sleeves_18crowns.

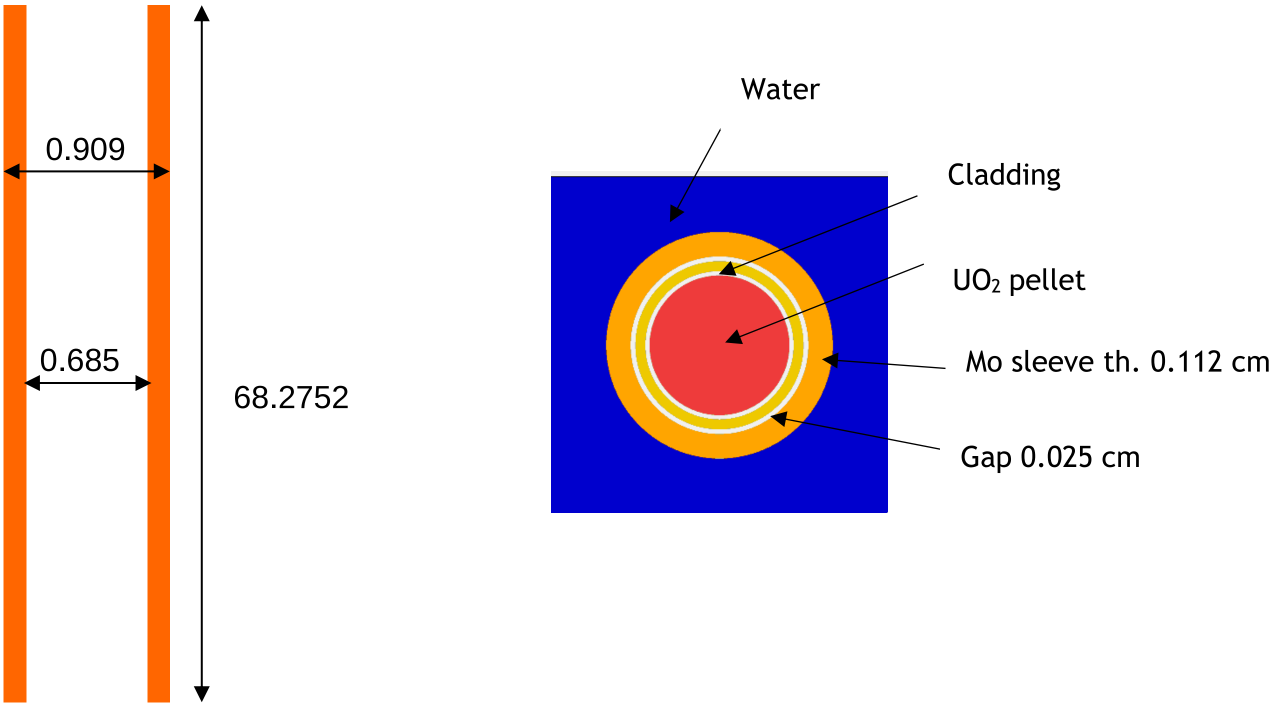

Figure 34. Cross cut views of Molybdenum sleeves - 7uPCX_547sleeves_18crowns.

Table 34: Characteristics of molybdenum sleeves.

	Gap between rod and sleeve (cm)	Internal radius (cm)	External radius (cm)	Height (cm)
Tube	0.025	0.342474	0.454474	68.2752

Geometry of configuration with 7uPCX rods and molybdenum sleeves – 7uPCX_547sleeves_th0.03_1039 rods_p1.6

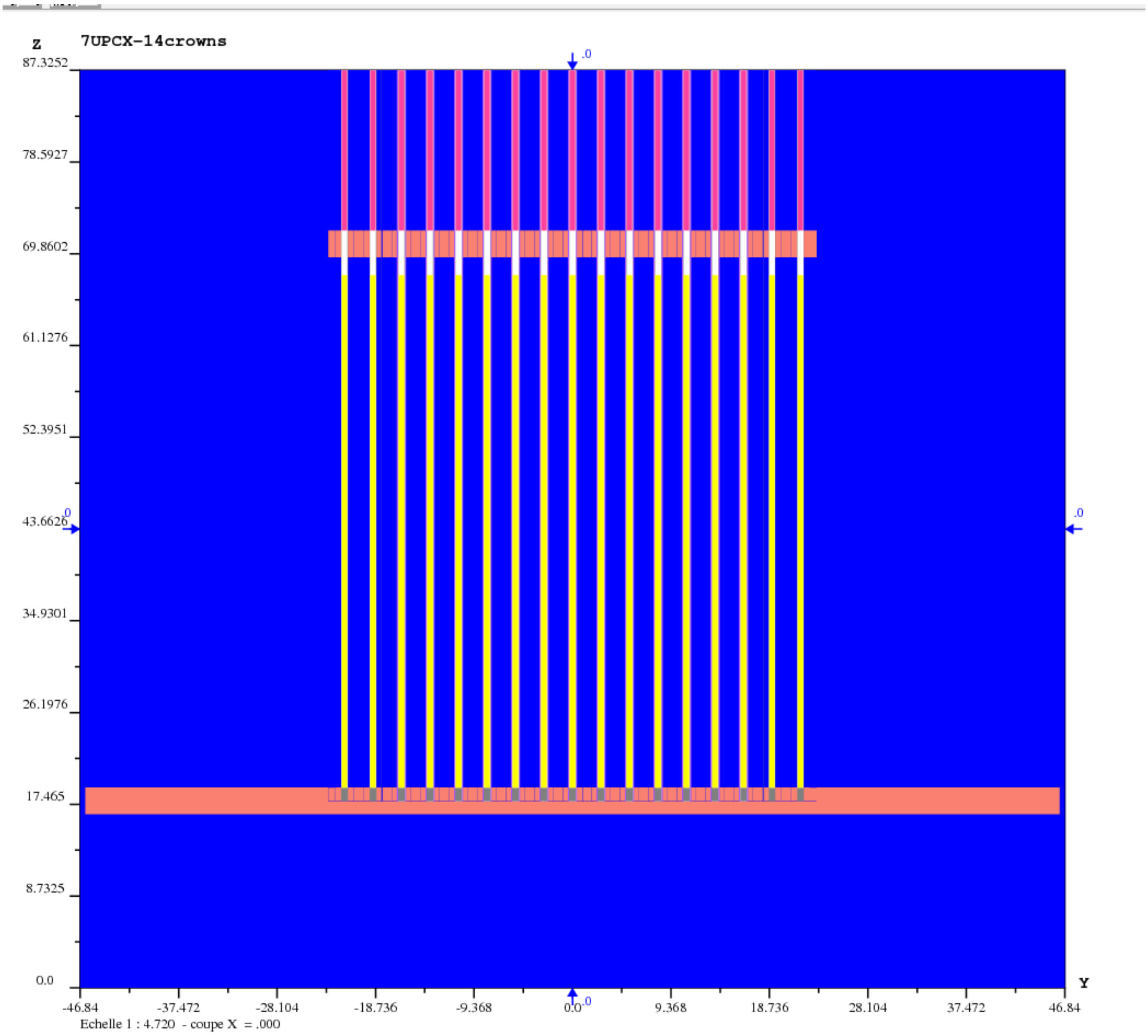

Figure 35. Vertical cross cut view of configuration with 7uPCX rods and Mo sleeves – 7uPCX_547sleeves_th0.03_1039rods_p1.6.

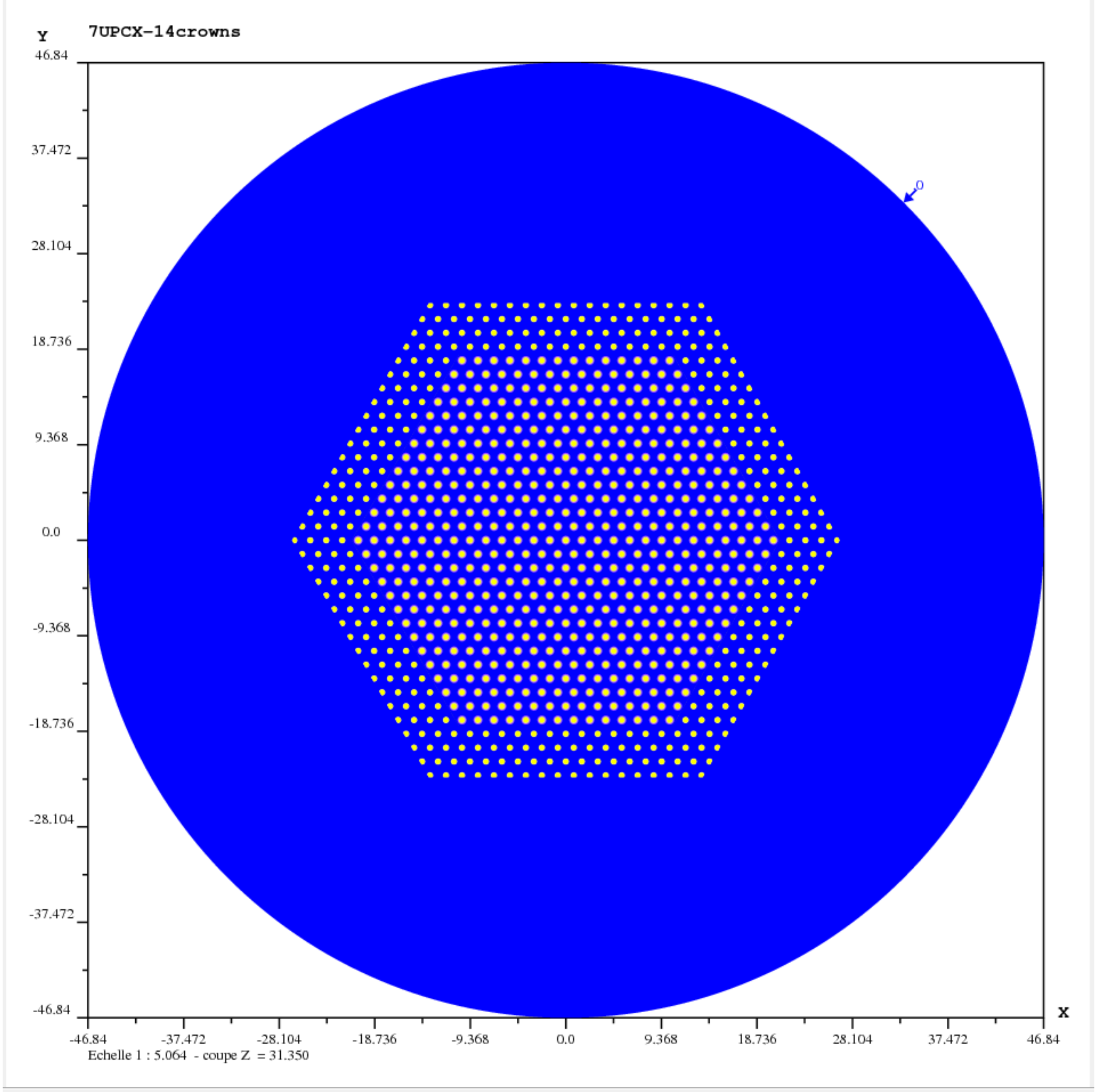

Figure 36. Horizontal cross cut view of configuration with 7uPCX rods and Mo sleeves - 7uPCX_547sleeves_th0.03_1039rods_p1.6.

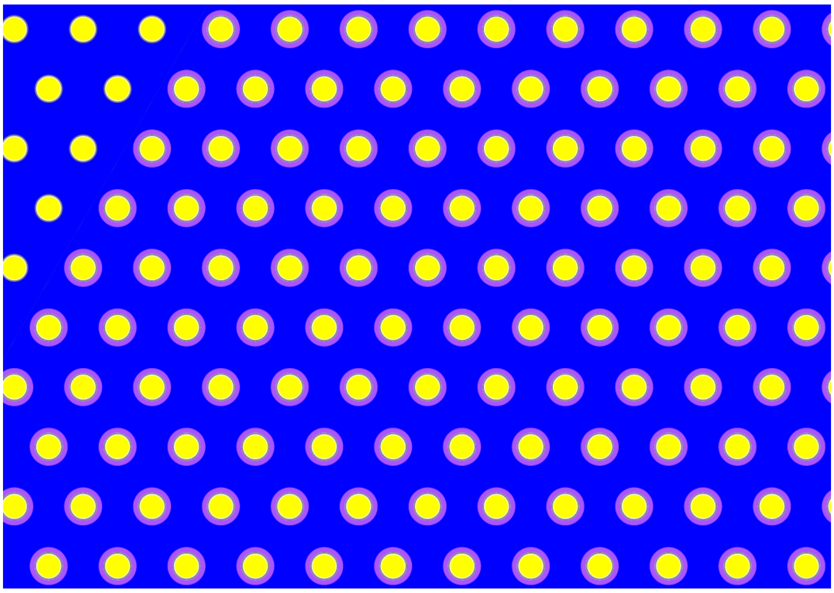

Figure 37. Horizontal cross cut view of configuration with 7uPCX rods and Mo sleeves - zoom - 7uPCX_547sleeves_th0.03_1039rods_p1.6.

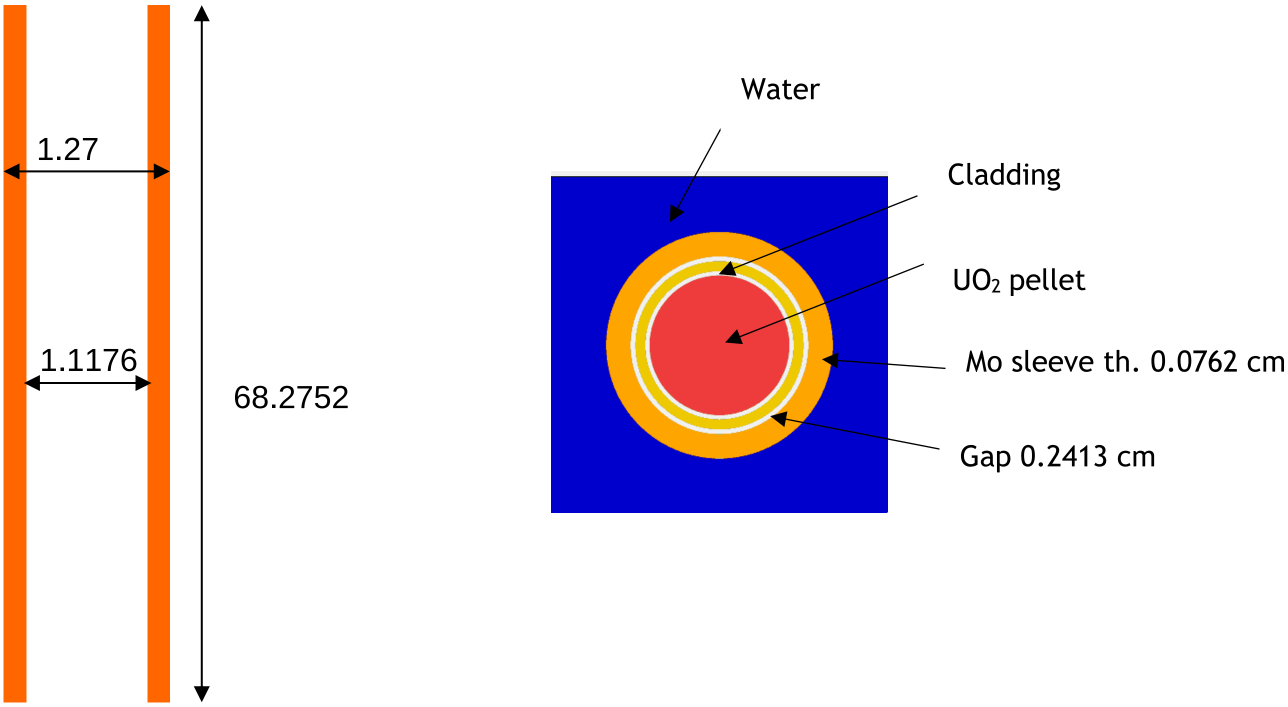

Figure 38. Cross cut views of Molybdenum sleeves - 7uPCX_547sleeves_th0.03_1039rods_p1.6.

Table 35: Characteristics of molybdenum sleeves.

	Gap between rod and sleeve (cm)	Internal radius (cm)	External radius (cm)	Height (cm)
Tube	0.2413	0.5588	0.635	68.2752

Geometry of configuration with BUCCX rods and molybdenum foils - 18 x 18_144

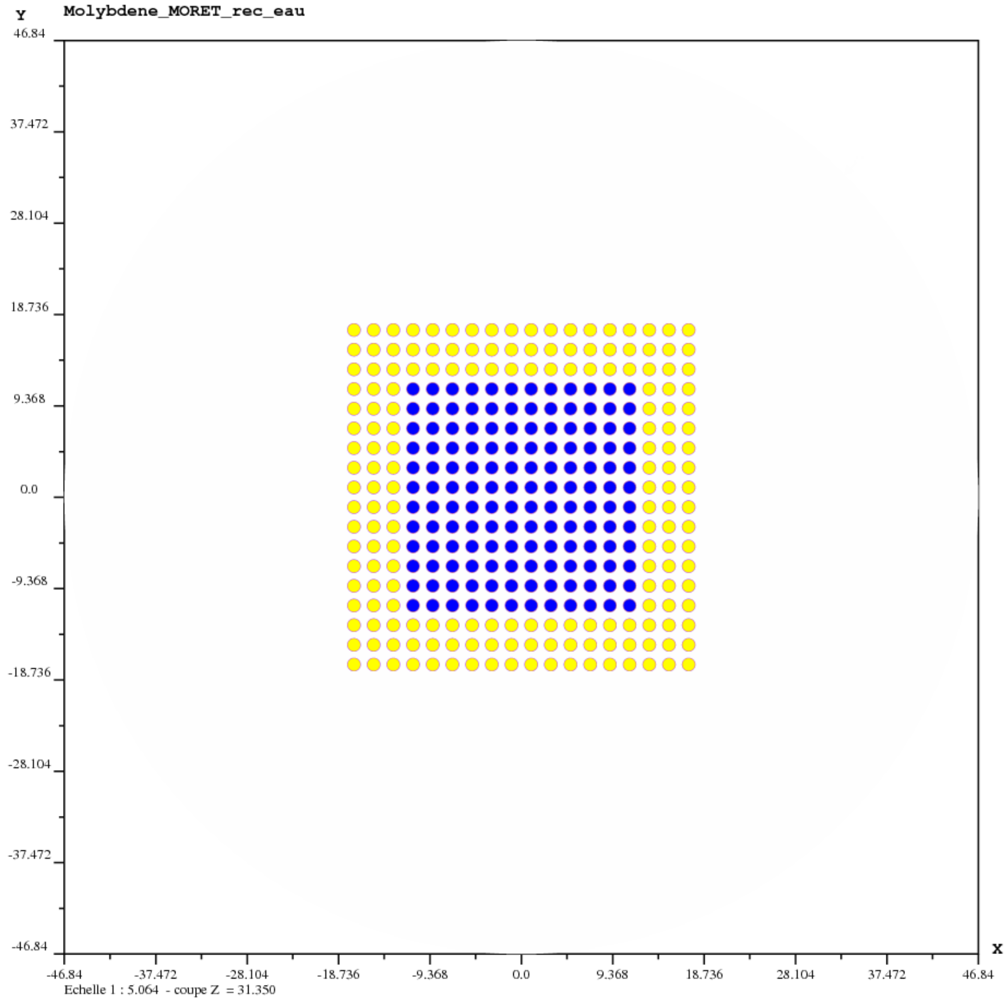

Figure 39. Horizontal Cross cut views of configuration with BUCCX rods and molybdenum foils - **18 x 18_144.**

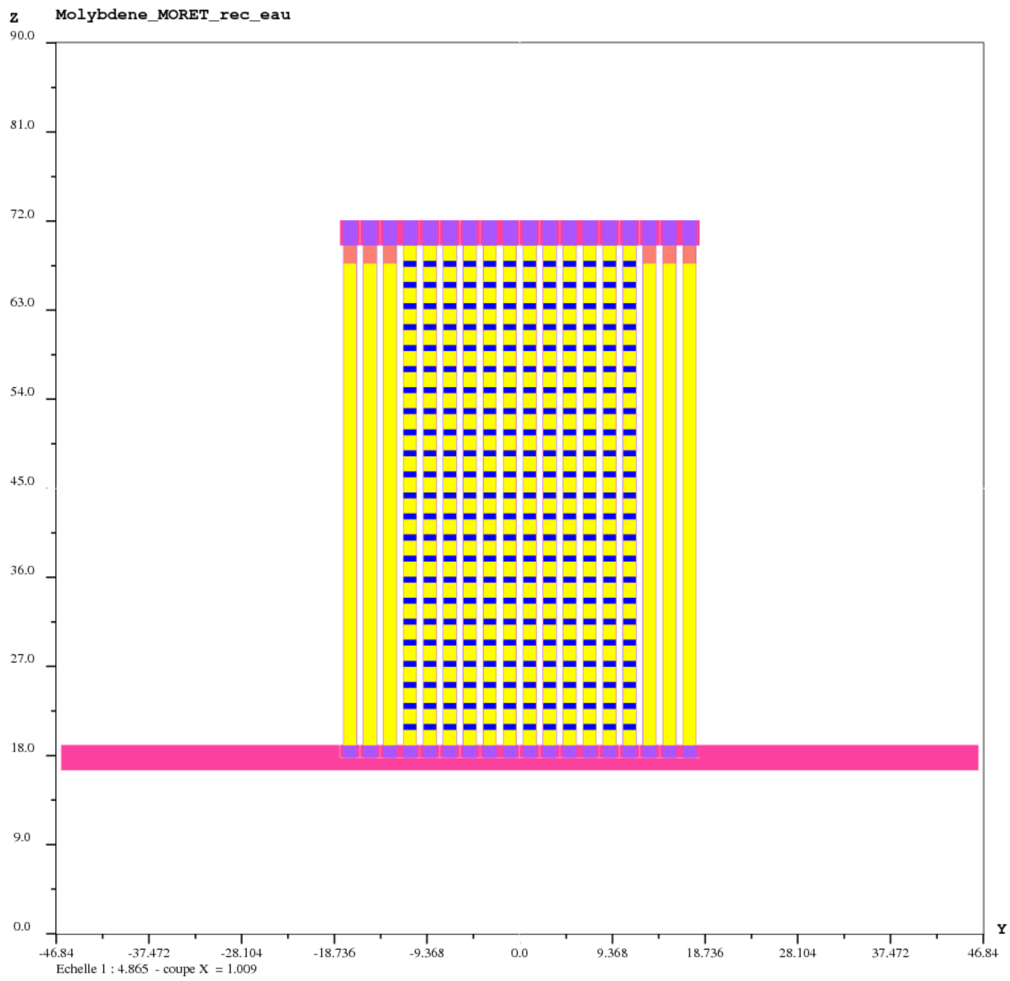

Figure 40. Vertical Cross cut views of configuration with BUCCX rods and molybdenum foils - **18 x 18_144.**

<u>Geometry of configuration with BUCCX rods and molybdenum sleeves around -</u>
505_7uPCX_216_BUCCX_hex_2.7

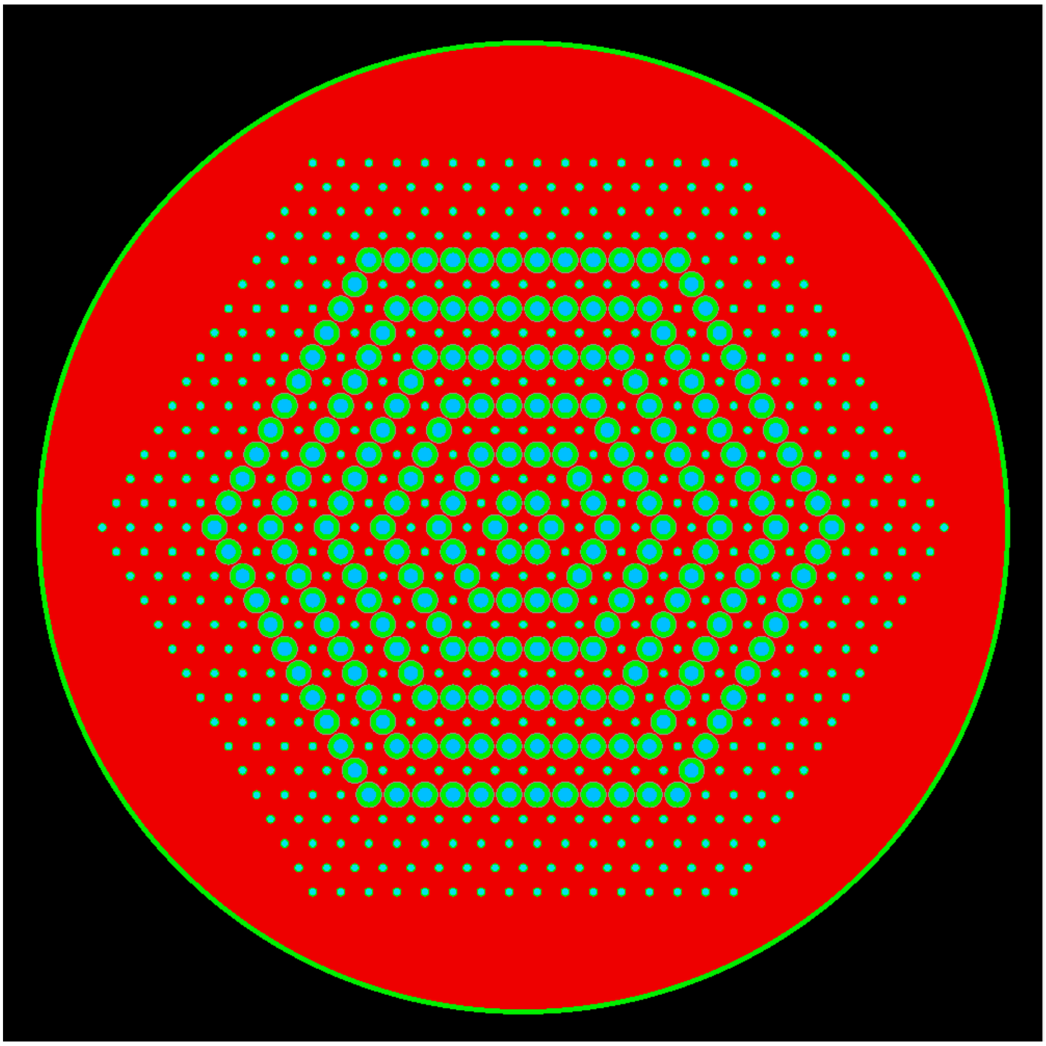

Figure 41. Horizontal Cross cut views of configuration with BUCCX rods surrounded by molybdenum sleeves – driver lattice of 7uPCX rods - **505_7uPCX_216_BUCCX_hex_2.7**

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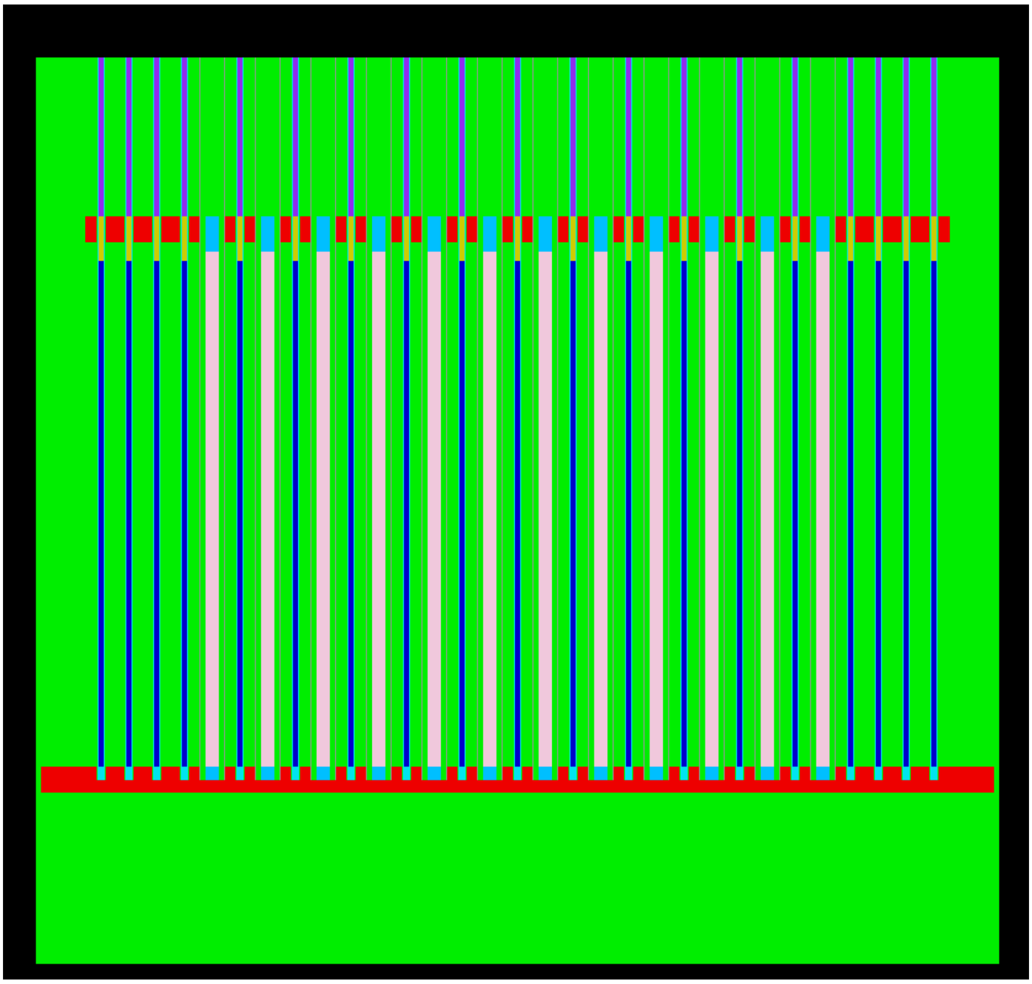

Figure 42. Vertical Cross cut views of configuration with BUCCX rods surrounded by molybdenum sleeves – driver lattice of 7uPCX rods - **505_7uPCX_216_BUCCX_hex_2.7**

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Input file for configuration with BUCCX rods and Mo foils – 18 x 18_144

```
DEBUT_MORET
Molybdene_MORET_rec_eau

ARRE
  ETAP ACTI 20
  KEFF SIGM 0.00030
FARR

CHIM
PONC
BIBL jeff311.xml
   EXCE MO92 endf70.xml
        MO94 endf70.xml
        MO95 endf70.xml
        MO96 endf70.xml
        MO97 endf70.xml
        MO98 endf70.xml
        MO100 endf70.xml FINE
TEMP 294

COMP Comb_4_31 CONC
  U234      5.1985E-06
  U235      1.0132E-03
  U236      5.1544E-06
  U238      2.2221E-02
  O16       4.6888E-02
FINC

COMP Comb_6_90 CONC
  U234     6.5539E-06
  U235     1.6010E-03
  U236     1.4632E-05
  U238     2.1296E-02
  O16      4.5837E-02
  AG       9.2319E-09
  B        2.3858E-07
  CD       1.2380E-08
  CO       2.1620E-08
  CR       2.5100E-06
  CU       2.1316E-07
  FE       1.0311E-05
  MN      2.8372E-07
  MO92 1.85E-08
  MO94 1.15E-08
  MO95 1.98E-08
  MO96 2.08E-08
  MO97 1.19E-08
  MO98 3.00E-08
  MO100      1.20E-08
  NI       3.4989E-06
  V        1.4813E-08
FINC

COMP Molybdene CONC
MO92 9.51986E-03
MO94 5.93388E-03
MO95 1.02127E-02
MO96 1.07002E-02
MO97 6.12633E-03
MO98 1.54794E-02
MO100 6.17765E-03
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FINC

COMP Water CONC
  H1-H2O    6.6625E-02
  O16       3.3313E-02
FINC

COMP Air CONC
  N         4.1985E-05
  O16       1.1263E-05
FINC

COMP Aluminium_6061 CONC
  AL        5.9015E-02
  CR        6.0979E-05
  CU        7.0365E-05
  MG        6.6899E-04
  SI        3.4736E-04
FINC

COMP Clad_Zr4 CONC
  ZR        4.2425E-02
  SN        4.8181E-04
  FE        1.4832E-04
  CR        7.5862E-05
  O16       3.0818E-04
FINC


FINChimie

*  ------------------------------------------------------------------
* Materiaux
*  1 - Fuel 4.31
*  2 - Fuel 6.90
*  3 - Rhodium
*  4 - Water
*  5 - Air
*  6 - Aluminium 6061
*  7 - Zr4
*  ------------------------------------------------------------------

GEOM
MODU 0

*Interieur cuve (total)

TYPE 1 CYLZ 46.84 45.0
VOLU 1 0 1 4 0. 0. 45.0

*Interieur cuve (eau)


*Plaque inferieur

TYPE 2 CYLZ 46.355 1.27
VOLU 2 1 2 6 0.0 0.0 17.78


*Crayons combustibles
TYPE 3 BOIT 18.162 18.162 27.14625
TROU 1 1 3 1 0.0 0.0 44.92625 ECRASE 1 2


FINM

MODU 1
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* universe
TYPE 1 BOIT 18.162 18.162 27.14625
VOLU 1 0 1 4 0 0 27.14625

*11 crayon vide
*12 crayon 4.31
*14 crayon Rh

* Volume maille - Air
TYPE 10 BOIT 1.009 1.009 27.14625
* VOLU 11 1 10 5 -17.153 -17.153 27.14625
VOLU 12 1 10 4 -17.153 -17.153 27.14625
VOLU 13 1 10 4 -17.153 -17.153 27.14625


*Grille haute (hauteur plateau detecteur - bas du trou)
TYPE 30 BOIT 1.009 1.009 1.27
* VOLU 31 11 30 6 -17.153 -17.153  53.0225
VOLU 32 12 30 6 -17.153 -17.153  53.0225
VOLU 33 13 30 6 -17.153 -17.153  53.0225

* TYPE 40 CYLZ 0.69109 1.27
* VOLU 41 31 40 5 -17.153 -17.153  53.0225

*Grille basse

TYPE 50 BOIT 1.009 1.009 0.635
* VOLU 51 21 50 6 -17.153 -17.153  0.635
VOLU 52 12 50 6 -17.153 -17.153  0.635
VOLU 53 13 50 6 -17.153 -17.153  0.635

* TYPE 60 CYLZ 0.69109 0.635
* VOLU 61 51 60 4 -17.153 -17.153  0.635

*Gaine

TYPE 70 CYLZ 0.69109 27.14625
VOLU 72 12 70 7 -17.153 -17.153  27.14625 ECRASE 2 32 52
VOLU 73 13 70 7 -17.153 -17.153  27.14625 ECRASE 2 33 53

*Air

TYPE 80 CYLZ 0.64895 25.24125
VOLU 82 72 80 5 -17.153 -17.153 26.51125
VOLU 83 73 80 5 -17.153 -17.153 26.51125

*Combustible

TYPE 92 CYLZ 0.63245 24.3312
VOLU 92 82 92 1 -17.153 -17.153 25.6012

TYPE 93 CYLZ 0.63245 25.2326
VOLU 93 83 93 1 -17.153 -17.153 26.5026

TYPE 103 CYLZ 0.63245 0.289
TYPE 113 CYLZ 0.62611 0.289


VOLU  103  93  103 5  -17.153    -17.153    3.1078
VOLU  113 103  113 3  -17.153    -17.153    3.1078


VOLU  123  93  103 5  -17.153    -17.153    5.2345
VOLU  133 123  113 3  -17.153    -17.153    5.2345


VOLU  143  93  103 5  -17.153    -17.153    7.3614
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VOLU  153 143  113 3  -17.153    -17.153    7.3614


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VOLU  173 163  113 3  -17.153    -17.153    9.4881


VOLU  183  93  103 5  -17.153    -17.153    11.6149
VOLU  193 183  113 3  -17.153    -17.153    11.6149


VOLU  203  93  103 5  -17.153    -17.153    13.7418
VOLU  213 203  113 3  -17.153    -17.153    13.7418


VOLU  223  93  103 5  -17.153    -17.153    15.8686
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VOLU  243  93  103 5  -17.153    -17.153    17.9953
VOLU  253 243  113 3  -17.153    -17.153    17.9953


VOLU  263  93  103 5  -17.153    -17.153    20.1221
VOLU  273 263  113 3  -17.153    -17.153    20.1221


VOLU  283  93  103 5  -17.153    -17.153    22.2489
VOLU  293 283  113 3  -17.153    -17.153    22.2489


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VOLU  313 303  113 3  -17.153    -17.153    24.3757


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VOLU  343  93  103 5  -17.153    -17.153    28.6293
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VOLU  363  93  103 5  -17.153    -17.153    30.7561
VOLU  373 363  113 3  -17.153    -17.153    30.7561


VOLU  383  93  103 5  -17.153    -17.153    32.8829
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VOLU  403  93  103 5  -17.153    -17.153    35.0098
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VOLU  443  93  103 5  -17.153    -17.153    39.2634
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VOLU  533 523  113 3  -17.153    -17.153    47.7705


VOLU  543  93  103 5  -17.153    -17.153    49.8974
VOLU  553 543  113 3  -17.153    -17.153    49.8974



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 INDP 0 0 1
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3 4   1     4 4   1     5 4   1     6 4   1     7 4   1     8 4   1     9 4
      1     10 4 1      11 4 1      12 4 1      13 4 1      14 4 1
3 5   1     4 5   1     5 5   1     6 5   1     7 5   1     8 5   1     9 5
      1     10 5 1      11 5 1      12 5 1      13 5 1      14 5 1
3 6   1     4 6   1     5 6   1     6 6   1     7 6   1     8 6   1     9 6
      1     10 6 1      11 6 1      12 6 1      13 6 1      14 6 1
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      1     10 8 1      11 8 1      12 8 1      13 8 1      14 8 1
3 9   1     4 9   1     5 9   1     6 9   1     7 9   1     8 9   1     9 9
      1     10 9 1      11 9 1      12 9 1      13 9 1      14 9 1
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      12 10 1            13 10 1            14 10 1
3 11 1 4 11 1 5 11 1 6 11 1 7 11 1 8 11 1 9 11 1 10 11 1           11 11 1
      12 11 1            13 11 1            14 11 1
3 12 1 4 12 1 5 12 1 6 12 1 7 12 1 8 12 1 9 12 1 10 12 1           11 12 1
      12 12 1            13 12 1            14 12 1
3 13 1 4 13 1 5 13 1 6 13 1 7 13 1 8 13 1 9 13 1 10 13 1           11 13 1
      12 13 1            13 13 1            14 13 1
3 14 1 4 14 1 5 14 1 6 14 1 7 14 1 8 14 1 9 14 1 10 14 1           11 14 1
      12 14 1            13 14 1            14 14 1

FINR

FINM


FING
GRAP X 0.0 FGRA
PEIN X 0.0
COULeur 7       1 JAUNe
                2 GRIS
                3 BLEU
                4 WHITe
                5 SAUMon
                6 BONBon
                 7 QUETsche

FGRA
GRAP X 1.009 FGRA
PEIN X 1.009 FGRA
GRAP Z 7.75 FGRA
```

```
PEIN Z 7.75 FGRA
GRAP Z 18.75 FGRA
PEIN Z 18.75 FGRA
GRAP Z 31.35 FGRA
PEIN Z 31.35 FGRA
GRAP Z 35.25 FGRA
PEIN Z 35.25 FGRA


SORTies
  SCORes
    ANNUle TOUS
    ACTI SEUL 2 BILAN_2G
    CARA
  FSCOres
FSORties




SOUR
 UNIF 50 MODU 1 FUNI
FINS


FIND

FIN_MORET
```

Input file for configuration with 7uPCX rods and Mo sleeves – 7uPCX_547sleeves_18crowns

```
DEBUT_MORET
7UPCX-14crowns


ARRE
  ETAP ACTI 200
  KEFF SIGM 0.00030
FARR

CHIM
PONC
BIBL endf70.xml
TEMP 294

COMP Comb_6_90 CONC
  U234      6.5539E-06
  U235      1.6010E-03
  U236      1.4632E-05
  U238      2.1296E-02
  O16       4.5837E-02
  AG        9.2319E-09
  B         2.3858E-07
  CD        1.2380E-08
  CO        2.1620E-08
  CR        2.5100E-06
  CU        2.1316E-07
  FE        1.0311E-05
  MN        2.8372E-07
  MO92 1.85E-08
  MO94 1.15E-08
  MO95 1.98E-08
  MO96 2.08E-08
  MO97 1.19E-08
  MO98 3.00E-08
  MO100       1.20E-08
  NI       3.4989E-06
  V         1.4813E-08
FINC

COMP Aluminium_cladding CONC
  AL        5.9668E-02
  SI        1.7561E-04
  FE        1.0303E-04
  CU        3.2339E-05
  MN        3.7407E-04
  ZN        1.2571E-05
FINC

COMP Water  CONC
  H1-H2O    6.6659E-02
  O16       3.3329E-02
FINC

COMP Air CONC
  N         4.1985E-05
  O16       1.1263E-05
FINC

COMP Aluminium_6061 CONC
  AL        5.8376E-02
  SI        4.1683E-04
  FE        1.8051E-04
```

```
  CU       7.9320E-05
  MN       2.6637E-05
  MG       6.9574E-04
  CR       6.2542E-05
  ZN       2.9839E-05
  TI       6.7918E-06
  V        3.1918E-06
FINC

COMP Polyethylene CONC
  H1-CH2   8.2755E-02
  C        4.1377E-02
FINC

COMP Molybdene CONC
MO92 9.51986E-03
MO94 5.93388E-03
MO95 1.02127E-02
MO96 1.07002E-02
MO97 6.12633E-03
MO98 1.54794E-02
MO100 6.17765E-03
FINC

COMP Comb_6_90_gaine CONC
  U234     6.5539E-06
  U235     1.6010E-03
  U236     1.4632E-05
  U238     2.1296E-02
  O16      4.5837E-02
  AG       9.2319E-09
  B        2.3858E-07
  CD       1.2380E-08
  CO       2.1620E-08
  CR       2.5100E-06
  CU       2.1316E-07
  FE       1.0311E-05
  MN       2.8372E-07
  MO92 1.85E-08
  MO94 1.15E-08
  MO95 1.98E-08
  MO96 2.08E-08
  MO97 1.19E-08
  MO98 3.00E-08
  MO100      1.20E-08
  NI      3.4989E-06
  V        1.4813E-08
FINC

COMP Clad_Zr4 CONC
  AL       5.9668E-02
  SI       1.7561E-04
  FE       1.0303E-04
  CU       3.2339E-05
  MN       3.7407E-04
  ZN       1.2571E-05
FINC


FINChimie

*  ---------------------------------------------------------------------
* Materiaux
*  1 - Fuel
*  2 - Aluminium cladding
*  3 - Water
*  4 - Air
```

```
*  5 - Aluminium 6061
*  6 - Polyethylene
*  7 - Mo
*  -----------------------------------------------------------------------

GEOM
MODU 0

*Interieur cuve (total)

TYPE 1 CYLZ 46.84 43.6626
VOLU 1 0 1 3 0. 0. 43.6626

*Interieur cuve (eau)


*Plaque inferieur

TYPE 2 CYLZ 46.355 1.27
VOLU 2 1 2 5 0.0 0.0 17.7


*Crayons combustibles
TYPE 3 HEXZ DIAM 46.8699 34.7726 0.0
TROU 1 1 3 1 0.0 0.0 52.5526 ECRASE 1 2  EECRA 1 16

* universe
TYPE 16 HEXZ DIAM 36.33 34.7726 0.0
VOLU 16 1 16 2 0 0 52.5526 ECRA 1 2
TROU 16 16 16 2 0 0 52.5526


FINM

MODU 1
* universe
TYPE 1 HEXZ DIAM 46.8699 34.7726 0.0
VOLU 1 0 1 3 0 0 34.7726
VOLU 17 1 1 3 0 0 34.7726


* Volume maille - eau 7UPCX
TYPE 10 HEXZ DIAM 1.56592 34.7726 90.0
VOLU 13 17 10 3 0 0 34.7726


*Grille haute (hauteur plateau detecteur - bas du trou)
TYPE 30 HEXZ DIAM 1.56592 1.27 90.0
VOLU 35 13 30 5 0 0  53.0352


*Grille basse

TYPE 50 HEXZ DIAM 1.56592 0.635 90.0
VOLU 55 13 50 5 0 0  0.635


*Gaine
TYPE 70 CYLZ 0.317474 34.7726
VOLU 730 13 70 2 0 0  34.7726 ECRA 2 35   55

*Air
TYPE 80 CYLZ 0.284519 34.1376
VOLU 830 730  80 4 0 0 35.4076

* FISSILE
TYPE 90 CYLZ 0.262814 24.39
```

```
VOLU 930 830  90 1 0 0 25.66


*CH2
TYPE 830 CYLZ 0.26289 7.62
VOLU 8400 830 830 6 0 0 61.9252



RESH
 MPRI 13
 DIMR 18 1
 INDP 0 0 0
FINR



FINM


MODU 2
* universe
TYPE 16 HEXZ DIAM  36.33 34.7726 0.0
VOLU 16 0 16 3 0 0 34.7726


* Volume maille - eau 7UPCX
TYPE 10 HEXZ DIAM 1.56592 34.7726 90.0
VOLU 13 16 10 3 0 0 34.7726


*Grille haute (hauteur plateau detecteur - bas du trou)
TYPE 30 HEXZ DIAM 1.56592 1.27 90.0
VOLU 33 13 30 5 0 0  53.0352

*Grille basse

TYPE 50 HEXZ DIAM 1.56592 0.635 90.0
VOLU 53 13 50 5 0 0  0.635

*surgaine
TYPE 203 CYLZ 0.454474 34.7726
VOLU 203 13 203 7 0 0  34.7726  ECRASE 2 33 53

* Gap
TYPE 213 CYLZ 0.342474  34.7726
VOLU 213 203 213 3 0 0  34.7726

*Gaine
TYPE 70 CYLZ 0.317474 34.7726
VOLU 73 213 70 2 0 0  34.7726

*Air
TYPE 80 CYLZ 0.284519 34.1376
VOLU 83 73  80 4 0 0 35.4076

* FISSILE
TYPE 90 CYLZ 0.262814 24.39
VOLU 93 83 90 1 0 0 25.66


*CH2
TYPE 830 CYLZ 0.26289 7.62
VOLU 840 83 830 6 0 0 61.9252
```

```
RESH
 MPRI 13
 DIMR 14 1
 INDP 0 0 0
FINR

FINM


FING

GRAP X 0.0 FGRA
PEIN X 0.0
COULeur 7 1 JAUNe
               2 GRIS
               3 BLEU
               4 WHITe
               5 SAUMon
               6 BONBon
             7 QUETsche
FGRA
GRAP X 0.67 FGRA
PEIN X 0.67 FGRA
GRAP Z 7.75 FGRA
PEIN Z 7.75 FGRA
GRAP Z 18.75 FGRA
PEIN Z 18.75 FGRA
GRAP Z 31.35 FGRA
PEIN Z 31.35 FGRA
GRAP Z 35.25 FGRA
PEIN Z 35.25 FGRA




SORTies

  SCORes
    ANNUle TOUS
    ACTI SEUL 2 BILAN_2G
    CARA
  FSCOres
SENS
EBIN  DEC238_SCALE
     SCHI
    SCOS
  ENDS
FSOR



SOUR
 UNIF 5 MODU 1 FUNI
FINS


FIND

FIN_MORET
```

Input file for configuration with 7uPCX rods and Mo sleeves – 7uPCX_547sleeves_1039rods_p1.6

```
DEBUT_MORET
7UPCX-14crowns


ARRE
  ETAP ACTI 100
       PASS 100
  KEFF SIGM 0.00020
FARR

CHIM
PONC
BIBL jeff311.xml
TEMP 294

COMP Comb_6_90 CONC
  U234     6.5539E-06
  U235     1.6010E-03
  U236     1.4632E-05
  U238     2.1296E-02
  O16     4.5837E-02
  AG      9.2319E-09
  B       2.3858E-07
  CD      1.2380E-08
  CO      2.1620E-08
  CR      2.5100E-06
  CU      2.1316E-07
  FE      1.0311E-05
  MN      2.8372E-07
  MO92  1.85E-08
  MO94  1.15E-08
  MO95  1.98E-08
  MO96  2.08E-08
  MO97  1.19E-08
  MO98  3.00E-08
  MO1001.20E-08
  NI      3.4989E-06
  V       1.4813E-08
FINC

COMP Aluminium_cladding CONC
  AL      5.9668E-02
  SI      1.7561E-04
  FE      1.0303E-04
  CU      3.2339E-05
  MN      3.7407E-04
  ZN      1.2571E-05
FINC

COMP Water  CONC
  H1-H2O   6.6659E-02
  O16     3.3329E-02
FINC

COMP Air CONC
  N       4.1985E-05
  O16     1.1263E-05
FINC

COMP Aluminium_6061 CONC
  AL      5.8376E-02
  SI      4.1683E-04
  FE      1.8051E-04
  CU      7.9320E-05
```

```
 MN      2.6637E-05
 MG      6.9574E-04
 CR      6.2542E-05
 ZN      2.9839E-05
 TI      6.7918E-06
 V       3.1918E-06
FINC

COMP Polyethylene CONC
 H1-CH2   8.2755E-02
 C        4.1377E-02
FINC

COMP Molybdene CONC
MO92    9.51986E-03
MO94    5.93388E-03
MO95    1.02127E-02
MO96    1.07002E-02
MO97    6.12633E-03
MO98    1.54794E-02
MO100   6.17765E-03


FINC

COMP Comb_6_90_gaine CONC
 U234     6.5539E-06
 U235     1.6010E-03
 U236     1.4632E-05
 U238     2.1296E-02
 O16      4.5837E-02
 AG       9.2319E-09
 B        2.3858E-07
 CD       1.2380E-08
 CO       2.1620E-08
 CR       2.5100E-06
 CU       2.1316E-07
 FE       1.0311E-05
 MN       2.8372E-07
 MO92  1.85E-08
 MO94  1.15E-08
 MO95  1.98E-08
 MO96  2.08E-08
 MO97  1.19E-08
 MO98  3.00E-08
 MO100 1.20E-08
 NI      3.4989E-06
 V       1.4813E-08
FINC

COMP Clad_Zr4 CONC
 AL      5.9668E-02
 SI      1.7561E-04
 FE      1.0303E-04
 CU      3.2339E-05
 MN      3.7407E-04
 ZN      1.2571E-05
FINC

COMP PERTUP CONC
 U234     6.5539E-06
 U235     1.60287E-03
 U236     1.4632E-05
 U238     2.12942E-02
 O16      4.5837E-02
 AG       9.2319E-09
```

```
 B       2.3858E-07
 CD       1.2380E-08
 CO       2.1620E-08
 CR       2.5100E-06
 CU       2.1316E-07
 FE       1.0311E-05
 MN       2.8372E-07
 MO92  1.85E-08
 MO94  1.15E-08
 MO95  1.98E-08
 MO96  2.08E-08
 MO97  1.19E-08
 MO98  3.00E-08
 MO100 1.20E-08
 NI     3.4989E-06
 V       1.4813E-08
 FINC

 COMP PERTUM CONC
 U234     6.5539E-06
 U235     1.59913E-03
 U236     1.4632E-05
 U238     2.12978E-02
 O16      4.5837E-02
 AG       9.2319E-09
 B       2.3858E-07
 CD       1.2380E-08
 CO       2.1620E-08
 CR       2.5100E-06
 CU       2.1316E-07
 FE       1.0311E-05
 MN       2.8372E-07
 MO92  1.85E-08
 MO94  1.15E-08
 MO95  1.98E-08
 MO96  2.08E-08
 MO97  1.19E-08
 MO98  3.00E-08
 MO100 1.20E-08
 NI     3.4989E-06
 V       1.4813E-08
FINC

FINChimie

*  -------------------------------------------------------------------
* Materiaux
*  1 - Fuel
*  2 - Aluminium cladding
*  3 - Water
*  4 - Air
*  5 - Aluminium 6061
*  6 - Polyethylene
*  7 - Mo
*  -------------------------------------------------------------------

GEOM
MODU 0

*Interieur cuve (total)

TYPE 1 CYLZ 46.84 43.6626
VOLU 1 0 1 3 0. 0. 43.6626

*Interieur cuve (eau)
```

```
*Plaque inferieur

TYPE 2 CYLZ 46.355 1.27
VOLU 2 1 2 5 0.0 0.0 17.7


*Crayons combustibles
TYPE 3 HEXZ DIAM 51.2751 34.7726 0.0
TROU 1 1 3 1 0.0 0.0 52.5526 ECRASE 1 2  EECRA 1 16

* universe
TYPE 16 HEXZ DIAM 37.4169 34.7726 0.0
VOLU 16 1 16 2 0 0 52.5526 ECRA 1 2
TROU 16 16 16 2 0 0 52.5526


FINM

MODU 1
* universe
TYPE 1 HEXZ DIAM 51.2751 34.7726 0.0
VOLU 1 0 1 3 0 0 34.7726
VOLU 17 1 1 3 0 0 34.7726


* Volume maille - eau 7UPCX
TYPE 10 HEXZ DIAM 1.6002 34.7726 90.0
VOLU 13 17 10 3 0 0 34.7726

* Maille Vide
VOLU 14 17 10 3 0 0 34.7726



*Grille haute (hauteur plateau detecteur - bas du trou)
TYPE 30 HEXZ DIAM 1.6002 1.27 90.0
VOLU 35 13 30 5 0 0  53.0352


*Grille basse

TYPE 50 HEXZ DIAM 1.6002 0.635 90.0
VOLU 55 13 50 5 0 0  0.635


*Gaine
TYPE 70 CYLZ 0.317474 34.7726
VOLU 730 13 70 2 0 0  34.7726 ECRA 2 35   55

*Air
TYPE 80 CYLZ 0.284519 34.1376
VOLU 830 730  80 4 0 0 35.4076

* FISSILE
TYPE 90 CYLZ 0.262814 24.39
VOLU 930 830  90 1 0 0 25.66


*CH2
TYPE 830 CYLZ 0.26289 7.62
VOLU 8400 830 830 6 0 0 61.9252
```

RESH
MPRI 13
DIMR 20 1
INDP 1 1 1
MSEC 14 102
-18 1 1
-18 0 1
-18 -1 1
-18 -2 1
-18 -3 1
-18 -14 1
-18 -15 1
-18 -16 1
-18 -17 1
-18 -18 1
1 -18 1
0 -18 1
-1 -18 1
-2 -18 1
-3 -18 1
-14 -18 1
-15 -18 1
-16 -18 1
-17 -18 1
20 1 1
19 0 1
18 -1 1
17 -2 1
16 -3 1
20 5 1
20 4 1
20 3 1
20 2 1
20 20 1
20 19 1
20 18 1
20 17 1
20 16 1
19 20 1
18 20 1
17 20 1
16 20 1
5 20 1
4 20 1
3 20 1
2 20 1
1 20 1
0 19 1
-1 18 1
-2 17 1
-3 16 1
-14 5 1
-15 4 1
-16 3 1
-17 2 1
-4 -18 1
-5 -18 1
-12 -18 1
-13 -18 1
-18 -4 1
-18 -5 1
-18 -12 1
-18 -13 1
-4 15 1
-5 14 1
-12 7 1

```
-13 6 1
15 20 1
14 20 1
7 20 1
6 20 1
20 15 1
20 14 1
20 7 1
20 6 1
15 -4 1
14 -5 1
3 -16 1
2 -17 1
5 -14 1
4 -15 1
7 -12 1
6 -13 1
-6 -18 1
-11 -18 1
-18 -6 1
-18 -11 1
-6 13 1
-11 8 1
13 20 1
8 20 1
20 13 1
20 8 1
13 -6 1
8 -11 1
12 20 1
9 20 1
20 12 1
20 9 1
-7 12 1
-10 9 1
-18 -7 1
-18 -10 1
-7 -18 1
-10 -18 1
12 -7 1
9 -10 1

FINR



FINM


MODU 2
* universe
TYPE 16 HEXZ DIAM  37.4169 34.7726 0.0
VOLU 16 0 16 3 0 0 34.7726


* Volume maille - eau 7UPCX
TYPE 10 HEXZ DIAM 1.6002 34.7726 90.0
VOLU 13 16 10 3 0 0 34.7726


*Grille haute (hauteur plateau detecteur - bas du trou)
TYPE 30 HEXZ DIAM 1.6002 1.27 90.0
VOLU 33 13 30 5 0 0  53.0352

*Grille basse
```

```
TYPE 50 HEXZ DIAM 1.6002 0.635 90.0
VOLU 53 13 50 5 0 0  0.635

*surgaine
TYPE 203 CYLZ 0.635 34.7726
VOLU 203 13 203 7 0 0  34.7726  ECRASE 2 33 53

* Gap
TYPE 213 CYLZ 0.5588 34.7726
VOLU 213 203 213 3 0 0  34.7726

*Gaine
TYPE 70 CYLZ 0.317474 34.7726
VOLU 73 213 70 2 0 0  34.7726

*Air
TYPE 80 CYLZ 0.284519 34.1376
VOLU 83 73  80 4 0 0 35.4076

* FISSILE
TYPE 90 CYLZ 0.262814 24.39
VOLU 93 83  90 1 0 0 25.66


*CH2
TYPE 830 CYLZ 0.26289 7.62
VOLU 840 83 830 6 0 0 61.9252



RESH
 MPRI 13
 DIMR 14 1
 INDP 0 0 0
FINR

FINM


FING

ASSO
PERTU 2
MILI 1 Comb_6_90
MILI 2 Aluminium_cladding
MILI 3 Water
MILI 4 Air
MILI 5 Aluminium_6061
MILI 6 Polyethylene
MILI 7 Molybdene


FINAS

GRAP X 0.0 FGRA
PEIN X 0.0
COULeur 7 1 JAUNe
                  2 GRIS
                  3 BLEU
                  4 WHITe
                  5 SAUMon
                  6 BONBon
            7 QUETsche
FGRA
GRAP X 0.67 FGRA
```

```
PEIN X 0.67 FGRA
GRAP Z 7.75 FGRA
PEIN Z 7.75 FGRA
GRAP Z 18.75 FGRA
PEIN Z 18.75 FGRA
GRAP Z 31.35 FGRA
PEIN Z 31.35 FGRA
GRAP Z 35.25 FGRA
PEIN Z 35.25 FGRA



SORTies

  SCORes
    ANNUle TOUS
    ACTI SEUL 2 BILAN_2G
    CARA
  FSCOres
SENS
EBIN  DEC238_SCALE
     SCHI
    SCOS
  ENDS
FSOR



SOUR
 UNIF 10 MODU 1 FUNI
FINS


FIND

FIN_MORET
```

Input file for configuration with BUCCX rods and Mo sleeves - 505_7uPCX_216_BUCCX_hex_2.7

```
DEBUT_MORET
COURONNE_MORET_reacteur_eau

ARRE
   CYCL
    PASS 20
    ETAP ACTI 600
*    KEFF SIGM 0.00030
FARR

CHIM
PONC
BIBL $bib
TEMP 294

COMP Comb_6_90 CONC
  U234     6.5539E-06
  U235     1.6010E-03
  U236     1.4632E-05
  U238     2.1296E-02
  O16      4.5837E-02
  AG       9.2319E-09
  B        2.3858E-07
  CD       1.2380E-08
  CO       2.1620E-08
  CR       2.5100E-06
  CU       2.1316E-07
  FE       1.0311E-05
  MN       2.8372E-07
  MO92         1.85E-08
  MO94         1.15E-08
  MO95         1.98E-08
  MO96         2.08E-08
  MO97         1.19E-08
  MO98         3.00E-08
  MO100 1.20E-08
   NI       3.4989E-06
  V        1.4813E-08
FINC

COMP Aluminium_cladding CONC
  AL       5.9668E-02
  SI       1.7561E-04
  FE       1.0303E-04
  CU       3.2339E-05
  MN       3.7407E-04
  ZN       1.2571E-05
FINC

COMP Water  CONC
  H1-H2O   6.6659E-02
  O16      3.3329E-02
FINC

COMP Air CONC
  N        4.1985E-05
  O16      1.1263E-05
FINC

COMP Aluminium_6061 CONC
  AL       5.8376E-02
  SI       4.1683E-04
  FE       1.8051E-04
  CU       7.9320E-05
  MN       2.6637E-05
  MG       6.9574E-04
  CR       6.2542E-05
```

```
  ZN       2.9839E-05
  TI       6.7918E-06
  V        3.1918E-06
FINC

COMP Polyethylene CONC
  H1-CH2   8.2755E-02
  C        4.1377E-02
FINC

COMP Molybdene CONC
MO92 9.51986E-03
MO94 5.93388E-03
MO95 1.02127E-02
MO96 1.07002E-02
MO97 6.12633E-03
MO98 1.54794E-02
MO100 6.17765E-03
FINC

COMP Comb_4_31 CONC
  U234      5.1985E-06
  U235      1.0132E-03
  U236      5.1544E-06
  U238      2.2221E-02
  O16       4.6888E-02
FINC

COMP Clad_Zr4 CONC
  ZR        4.24250E-02
  SN        4.81810E-04
  FE        1.48320E-04
  CR        7.58620E-05
  O16       3.08180E-04
FINC


FINChimie

*  ---------------------------------------------------------------------
* Materiaux
*  1 - Fuel
*  2 - Aluminium cladding
*  3 - Water
*  4 - Air
*  5 - Aluminium 6061
*  6 - Polyethylene
*  7 - Mo
*  ---------------------------------------------------------------------

GEOM
MODU 0

*Interieur cuve (total)

TYPE 1 CYLZ 46.84 43.6626
VOLU 1 0 1 3 0. 0. 43.6626

*Interieur cuve (eau)


*Plaque inferieur

TYPE 2 CYLZ 46.355 1.27
VOLU 2 1 2 5 0.0 0.0 17.78


*Crayons combustibles
TYPE 3 HEXZ DIAM 72.9 34.7726 0.0  * le -0.5 correspond à un biais pour ne pas avoir le début
des prochaines mailles extérieures, affiner geometrie par calcul exact in fine
TROU 1 1 3 1 0.0 0.0 52.5526 ECRASE 1 2


FINM
```

```
MODU 1
* universe
TYPE 1 HEXZ DIAM 72.9 34.7726 0.0  * le -0.5 correspond à un biais pour ne pas avoir le début
des prochaines mailles extérieures, affiner geometrie par calcul exact in fine
VOLU 1 0 1 3 0 0 34.7726


* Volume maille - eau 7UPCX
TYPE 10 HEXZ DIAM 2.7 34.7726 90.0
VOLU 13 1 10 3 0 0 34.7726                    * crayon 7PUCX
* partie surgaine 7UPCX - devient de l'eau pour l'instant
*TYPE 203 CYLZ 0.44665 34.7726
*VOLU 203 13 203 3 0 0  34.7726 ECRASE 2 33 53 * surgaine, materiau 7 si surgaine en
molybdene, eau désormais
TYPE 213 CYLZ 0.318  34.7726                  * air interstitiel surgaine gaine, désormais eau
VOLU 213 13 213 3 0 0  34.7726 ECRASE 2 33 53
TYPE 70 CYLZ 0.317474 34.7726                 * gaine 7PUCX
VOLU 73 213 70 2 0 0  34.7726
TYPE 80 CYLZ 0.284519 34.1376                 * forme air dans gaine 7PUCX
VOLU 83 73 80 4 0 0 35.4076                   * air dans gaine 7PUCX
TYPE 830 CYLZ 0.26289 7.62                    * forme polyethylene 7PUCX
VOLU 840 83 830 6 0 0 61.9252                 * polyethylene 7PUCX
TYPE 90 CYLZ 0.262814 24.3312                   * forme combustible 7PUCX
VOLU 93 83  90 1 0 0 25.6012                    * combustible 7PUCX
TYPE 30 HEXZ DIAM 2.7 1.27 90.0
VOLU 33 13 30 5 0 0  53.0352                  *  grille aluminium haute 7PUCX
TYPE 50 HEXZ DIAM 2.7 0.635 90.0
VOLU 53 13 50 5 0 0  0.635                    *  grille aluminium basse 7PUCX



*Volume maille -eau BUCCX
VOLU 150 1 10 3 0 0 34.7726                    * crayon BUCCX en eau
TYPE 204 CYLZ 1.270442407 34.7726               * epaisseur de surgaine = strictement
inferieure  a moitie du pas et superieure a claddind + air de 0.691616
* partie surgaine BUCCX
VOLU 204 150 204 7 0 0  34.7726 ECRASE 2 350 550 * surgaine materiau 7 en molybdène
TYPE 205 CYLZ 1.18109 34.7726
VOLU 205 204 205 3 0 0  34.7726                * eau gaine/surgaine = epaisseur 0.49 cm
TYPE 700 CYLZ 0.69109 27.14625
VOLU 750 205 700 9 0. 0.  27.14625             * gaine/cladding en zirco des BUCCX, ecrase la
grille superieur en aluminium
TYPE 950 CYLZ 0.63245 24.7808
VOLU 950 750 950 8 0. 0. 26.0508               * combustible BUCCX

*Grille haute (hauteur plateau detecteur - bas du trou)
TYPE 300 HEXZ DIAM 2.7 1.27 90.0
VOLU 350 150 300 5 0 0 53.0352                 * grille aluminium haute BUCCX
*Grille basse
TYPE 500 HEXZ DIAM 2.7 0.635 90.0
VOLU 550 150 500 5 0 0  0.635                  * grille aluminium basse BUCCX

RESH
 MPRI 13
 DIML 17 1
 LAYE 0
13     13     13     13     13     13     13     13     13     13     13     13     13
       13     13     13     13

13     13     13     13     13     13     13     13     13     13     13     13     13
       13     13     13     13     13

13     13     13     13     13     13     13     13     13     13     13     13     13
       13     13     13     13     13     13

13     13     13     13     13     13     13     13     13     13     13     13     13
       13     13     13     13     13     13     13

13     13     13     13     13     13     13     13     13     13     13     13     13
       13     13     13     13     13     13     13     13

13     13     13     13     13     150    150    150    150    150    150    150    150
       150    150    150    150    13     13     13     13     13
```

13	13	13	13	13	150	13	13	13	13	13	13	13
	13	13	13	13	150	13	13	13	13	13		
13	13	13	13	13	150	13	150	150	150	150	150	150
	150	150	150	150	13	150	13	13	13	13	13	
13	13	13	13	13	150	13	150	13	13	13	13	13
	13	13	13	13	150	13	150	13	13	13	13	13
13	13	13	13	13	150	13	150	13	150	150	150	150
	150	150	150	150	13	150	13	150	13	13	13	13
	13											
13	13	13	13	13	150	13	150	13	150	13	13	13
	13	13	13	13	150	13	150	13	150	13	13	13
	13	13										
13	13	13	13	13	150	13	150	13	150	13	150	150
	150	150	150	150	13	150	13	150	13	150	13	13
	13	13	13									
13	13	13	13	13	150	13	150	13	150	13	150	13
	13	13	13	13	150	13	150	13	150	13	150	13
	13	13	13	13								
13	13	13	13	13	150	13	150	13	150	13	150	13
	150	150	150	150	13	150	13	150	13	150	13	150
	13	13	13	13	13							
13	13	13	13	13	150	13	150	13	150	13	150	13
	150	13	13	13	150	13	150	13	150	13	150	13
	150	13	13	13	13	13						
13	13	13	13	13	150	13	150	13	150	13	150	13
	150	13	150	150	13	150	13	150	13	150	13	150
	13	150	13	13	13	13	13					
13	13	13	13	13	150	13	150	13	150	13	150	13
	150	13	150	13	150	13	150	13	150	13	150	13
	150	13	150	13	13	13	13	13				
13	13	13	13	13	150	13	150	13	150	13	150	13
	150	13	150	150	13	150	13	150	13	150	13	150
	13	150	13	13	13	13	13					
13	13	13	13	13	150	13	150	13	150	13	150	13
	150	13	13	13	150	13	150	13	150	13	150	13
	150	13	13	13	13	13						
13	13	13	13	13	150	13	150	13	150	13	150	13
	150	150	150	150	13	150	13	150	13	150	13	150
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INSTITUT
DE RADIOPROTECTION
ET DE SÛRETÉ NUCLÉAIRE

Siège social : 31 av. de la division Leclerc – 92260 Fontenay-aux-Roses
Standard +33 (0)1 58 35 88 88 – RCS Nanterre B 440 546 018