Criticality Experiments with Tightly Packed Lattices of Low-Enriched UO_2 Rods

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Abstract

Critical experiments dealing with "tightly packed lattices" were carried out in the testing equipment "Apparatus B" of the C.E.A experimental criticality facility at Valduc. They involved water-moderated low-enriched UO_2 fuel rods arrays reflected by water or polyethylene. These configurations were performed with different square pitches corresponding to a range of EALF values (Energy of Average Lethargy causing Fission) from 0.106 to 0.899 eV.

These experiments were sub-critical approaches extrapolated to critical with the multiplication factor reached being very close to 1.000. All 27 experiments presented in this paper are acceptable for use as benchmark experiments.

These experiments have been investigated with CRISTAL V1.0 criticality package using nuclear data based on the JEF2.2 data file. Calculation-experiments comparison has highlighted a small under-prediction (less than 0.5 %) for under-moderated lattices, whereas for well-thermalised ones, a good agreement is observed. Moreover, no visible trend has been noticed with the CH_2 reflector, allowing being confident about the accuracy of the CH_2 cross-sections in thermal and epithermal energy range.

KEYWORDS: critical experiments, low-moderated, UO_2 rods, polyethylene reflector, heterogeneity, water holes

1. Introduction

Twenty-seven experiments dealing with low-enriched UO_2 lattices were carried out from 1998 to 1999 in the testing equipment "Apparatus B" of the C.E.A experimental criticality facility at Valduc, in the framework of the IRSN and AREVA-NC Common Interest Program.

Three mains configurations dealing with different square pitches were studied:

- water-moderated and water-reflected tightly packed lattices,
- water-moderated lattices with a water or a CH_2 reflector,
- water-moderated lattices with water holes.

These experiments will be proposed for the next I.C.S.B.E.P. (International Criticality Safety Benchmark Evaluation Project) handbooks [1].

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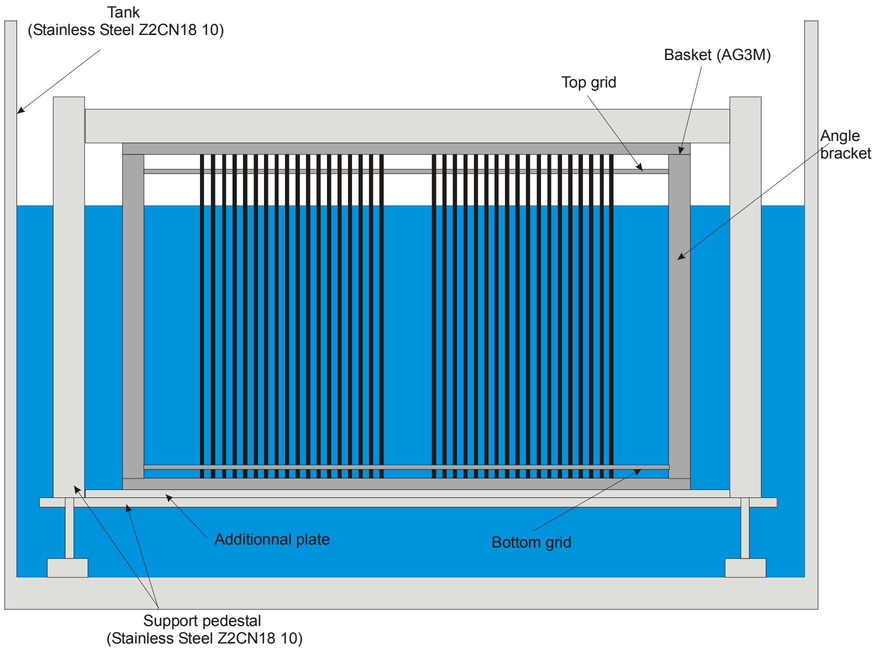
2. Description of Experimental Configuration

The experimental configuration (see Fig. 1) involved an array of low-enriched UO_2 fuel rods held by an aluminium (AG3M) basket placed on a stainless steel (Z2CN18-10) pedestal inside a parallelepiped tank, which was itself located on the floor in the middle (approximately) of a large room.

Figure 1 : Experimental device



These experiments were sub-critical approaches to within 0.1 % in reactivity of critical, extrapolated to critical conditions. Multiplication was determined by six BF3 neutron counters, which provided the counting rate M. The 1/M method was used to perform the extrapolation of sub-critical height measurements to the critical height. The water height was provided by a needle of measurement, which followed the free upper water level. The zero-level measurement was given from the bottom of the fuel rod fissile column.

Fuel rods were composed of low-enriched UO_2 pellets (density : 10.38 +/- 0.04 g/cm^3) clad with Zircaloy-4. The fuel column, 90 cm height, was composed of about 1.495 cm long pellets. The overall rod length was 102 cm. Each rod had an outer radius of 0.475 cm, an inner radius of 0.418 cm and the fuel pellet radius was 0.395 cm. A stainless steel spring maintained pellets in contact with each other. The uranium isotopic composition is given in Tab. 1 below.

Table 1 : Uranium isotopic composition

Isotopes	% (Weight) +/- 2 σ
^{234}U	0.0303 +/- 0.001
^{235}U	4.738 +/- 0.004
^{236}U	0.1360 +/- 0.001
^{238}U	95.095 +/- 0.02

2.1 Water-moderated and water-reflected tightly packed lattices

The main purpose of these experiments is to contribute to the validation of criticality calculation codes for low-water-moderated UO_2 lattices.

Four experiments (see Tab. 2) were performed for moderation ratios of about 1 and 0.9, of which all are acceptable for use as benchmark experiments.

Table 2 : Main characteristics of the critical experiments

Case number	Pitch (cm)	Along Edge	Water temperature (°C)	Critical water height (cm)*
1	1.1	36 x 35	20	57.323 +/- 0.090
2	1.1	33 x 33	19	74.019 +/- 0.147
3	1.1	32 x 32	20	86.929 +/- 0.041
4	1.075	35 x 35	20	87.286 +/- 0.038

**The given uncertainties corresponded to 2 σ*

Experimental uncertainties effects on the multiplication factor (k_{eff}) were evaluated following the I.C.S.B.E.P. approach.

In 1995, the aluminium clad of UO_2 fuel rods usually used in Valduc experiments [1] was replaced by a Zircaloy clad. Meanwhile, different chemical analysis (O/U ratio, impurities, uranium isotopic content) and various measurements were carried out on surplus pellets. Moreover, some measurements were done on about 100 rods (one on the top, one on the middle and one on the bottom of each rod) to determine the clad outer diameter and its associated uncertainty.

The uncertainty on the measured critical water height given in Tab.2 included on the one hand, the water height measurement uncertainty and the counting equipment accuracy, and on the other hand, the uncertainty of the extrapolation method.

Sensibility calculations have been carried out to assess the reactivity effect associated with one standard deviation (1 σ) for each parameter uncertainty. The total estimated uncertainty, which was calculated as the quadratic sum of all Δk_{eff} values, doesn't exceed 0.1 % (1σ). Since low moderation ratios were involved, the fuel rods positioning uncertainty (mainly due to the grid holes diameter) is the most important part of the global uncertainty (about 0.07 %).

2.2 Water-moderated lattices with a water or a CH2 reflector,

Four series of experiments (9 configurations) were performed with UO_2 lattices with various square pitches (see Tab. 3) :

- water-reflected rods arrays with a square pitch of 1.6 cm (3 experiments),
- CH_2-reflected rods arrays with a square pitch of 1.6 cm (3 experiments),
- CH_2-reflected rods arrays with a square pitch of 1.1 cm (2 experiments),
- CH_2-reflected rods arrays with a square pitch of 1.075 cm (1 experiment).

Except for the first ones, which were only water-reflected, the fourth lateral sides of the array are surrounded with 19.6 cm thick polyethylene screens (see Fig. 2). All are acceptable for use as benchmark experiments.

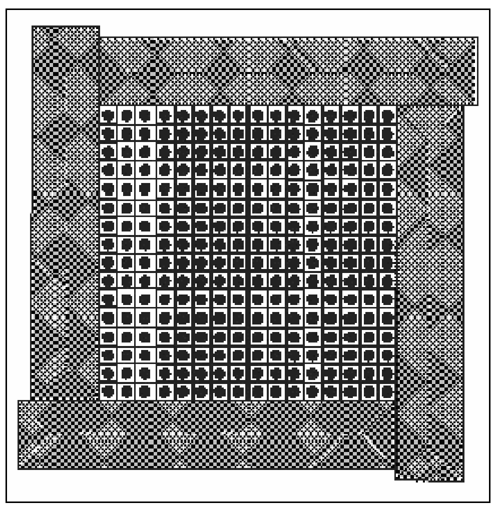
These 9 experiments, associated with the four previously described, intend to contribute to the validation of CH_2 cross sections in thermal and epithermal spectra.

Table 3 : Main characteristics of the critical experiments

Case number	Lattice pitch (cm)	Along Edge	Reflector	Water temperature (°C)	Critical water height +/- 2 σ (cm)
1	1.6	17 x 17	Water	19	60.479 +/- 0.052
2	1.6	16 x 16	Water	17	91.523 +/- 0.060
3	1.6	16 x 17	Water	17	71.836 +/- 0.050
4	1.6	17 x 17	CH_2	19	56.293 +/- 0.872*
5	1.6	16 x 16	CH_2	19	81.616 +/- 0.889*
6	1.6	16 x 17	CH_2	19	65.765 +/- 0.863*
7	1.1	33 x 33	CH_2	19	69.431 +/- 0.864*
8	1.1	32 x 32	CH_2	20	81.854 +/- 0.872*
9	1.075	35 x35	CH_2	20	82.227 +/- 0.862*

** The uncertainty on the measured critical water height also included the uncertainty due to the CH_2 reflectors position.*

Figure 2: Horizontal cross section of the CH_2-reflected configuration



As previously done, experimental uncertainties effects on the k_{eff} were evaluated.

The uncertainty due to the CH_2 reflector position was determined upon nine reproducibility measurements. They were performed for the 35 x 35 rods array with square pitch of 1.075 cm. The uncertainty on the average critical water height was equal to two standard deviations on the critical water heights given by the 6 counters used. Finally, the reproducibility value due to the polyethylene reflectors positions was estimated to be 0.804 cm (2 σ).

Moreover, the effects of CH2 reflectors height and thickness have been assessed for case 7 and 9. The calculated reactivity worth was lower than 0.001 % for these cases. Consequently, uncertainties due to the height and the thickness of CH_2 reflectors were not considered in the total estimated uncertainty.

Finally, the global experimental uncertainty (combination of 1 σ basic uncertainties) was estimated to be less than 0.05 % (1 σ) for cases 1 to 3 and about 0.1 % for cases 4 to 9.

2.3 Water-moderated lattices with water holes

These experiments involved an array of 2 x 2 UO_2 fuel rods assemblies with square pitches studied previously. The water gap between the assemblies varied and some fuel rods could be removed at the corners of each assembly in order to study the physical effect of water holes in low-moderated UO_2 rods arrays. These experiments intended to contribute to the validation of heterogeneous arrays, as BWR lattices.

Sixteen experiments involving different configurations (see Fig. 3) were performed for square pitches of 1.05 and 1.075 cm. Fourteen are acceptable for use as benchmark experiments (two of them did not reach criticality). Critical configurations are described in Tab. 4.

Figure 3: Horizontal cross section of the experimental configurations

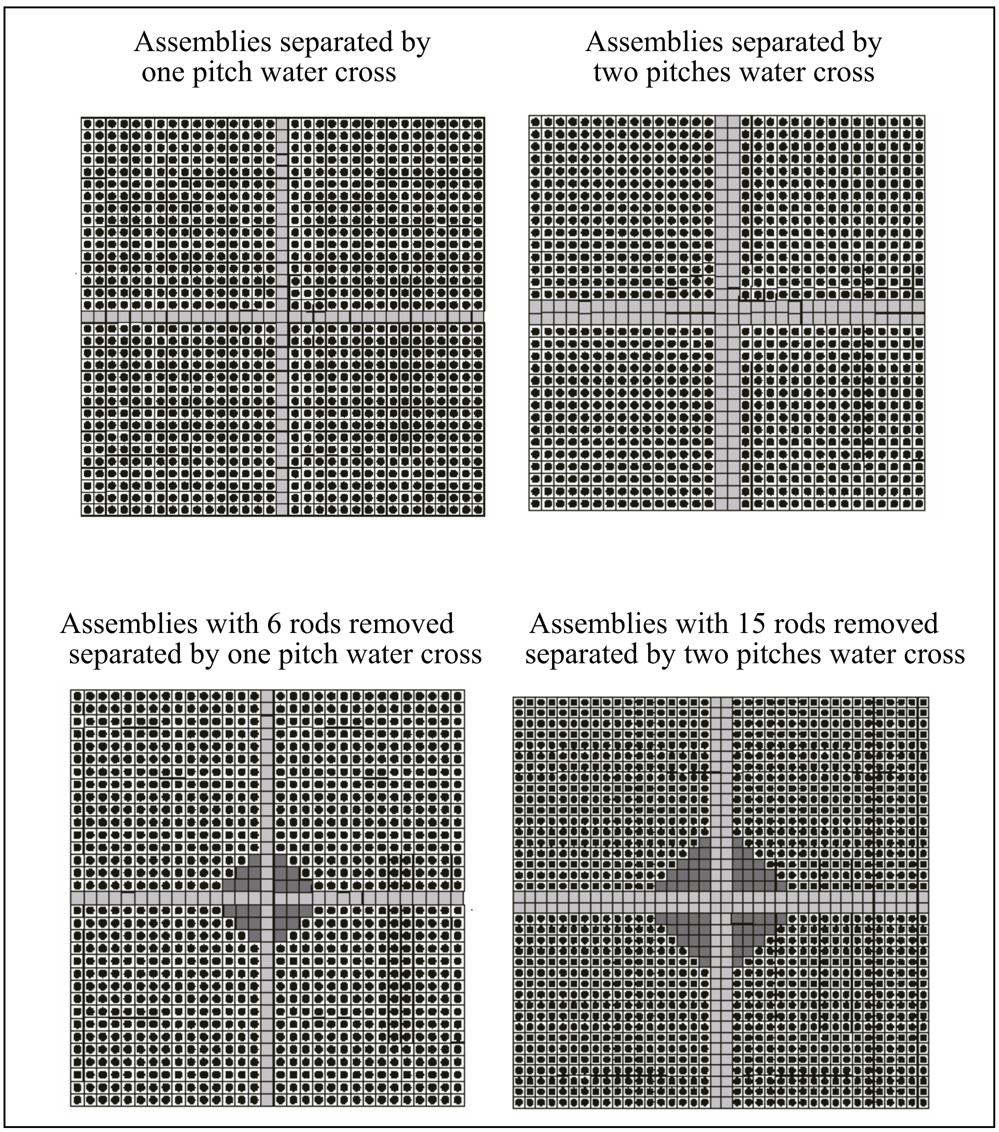


Table 4 : Main characteristics of the critical experiments

Case number	Lattice pitch (cm)	Configuration	Number of rods	Water temperature (°C)	Critical water height +/- 2 σ (cm)
1	1.05	Assemblies with 6 rods removed separated by 2 pitches	1260	21	58.164 +/- 0.042
2	1.05		1132	21	68.342 +/- 0.045
3	1.05		1000	21	89.548 +/- 0.082
4	1.075	Assemblies separated by 1 pitch	1024	18	65.092 +/- 0.064
5	1.075		900	18	84.887 +/- 0.067
6	1.075	Assemblies with 6 rods removed separated by 1 pitch	1000	18	72.029 +/- 0.059
7	1.075		936	19	83.554 +/- 0.060
8	1.075		906	21	92.261 +/- 0.066
9	1.075	Assemblies separated by 2 pitches	900	19	62.859 +/- 0.053
10	1.075		784	19	82.062 +/- 0.076
11	1.075		756	20	91.785 +/- 0.270*
12	1.075	Assemblies with 15 rods removed separated by 2 pitches	1236	20	68.393 +/- 0.048
13	1.075		1164	21	77.522 +/- 0.067
14	1.075		1130	21	83.438 +/- 0.057

**This relatively high value is due to the incomplete stabilization of neutron counters*

Experimental uncertainties effects on the multiplication factor (k_{eff}) were evaluated and don't exceed 0.1 % (1σ).

3. Calculation results

All these experiments have been investigated with the CRISTAL V1.0 criticality package [3], which consists of two calculation routes dealing with nuclear data based on the JEF 2.2 data file:

- a standard route based on a multi-group formulation of cross-sections using the APOLLO2 cell code and the MORET4 Monte Carlo code. The assembly code APOLLO2 is used for self-shielding and for flux calculations. Then, self-shielded, and eventually homogenized cross-sections, are used in the MORET4 Monte Carlo code for 3D calculations with a general Pn-like anisotropy representation,
- a reference route based on the TRIPOLI4 3D Monte Carlo code using a continuous-energy library.

3.1 Model description

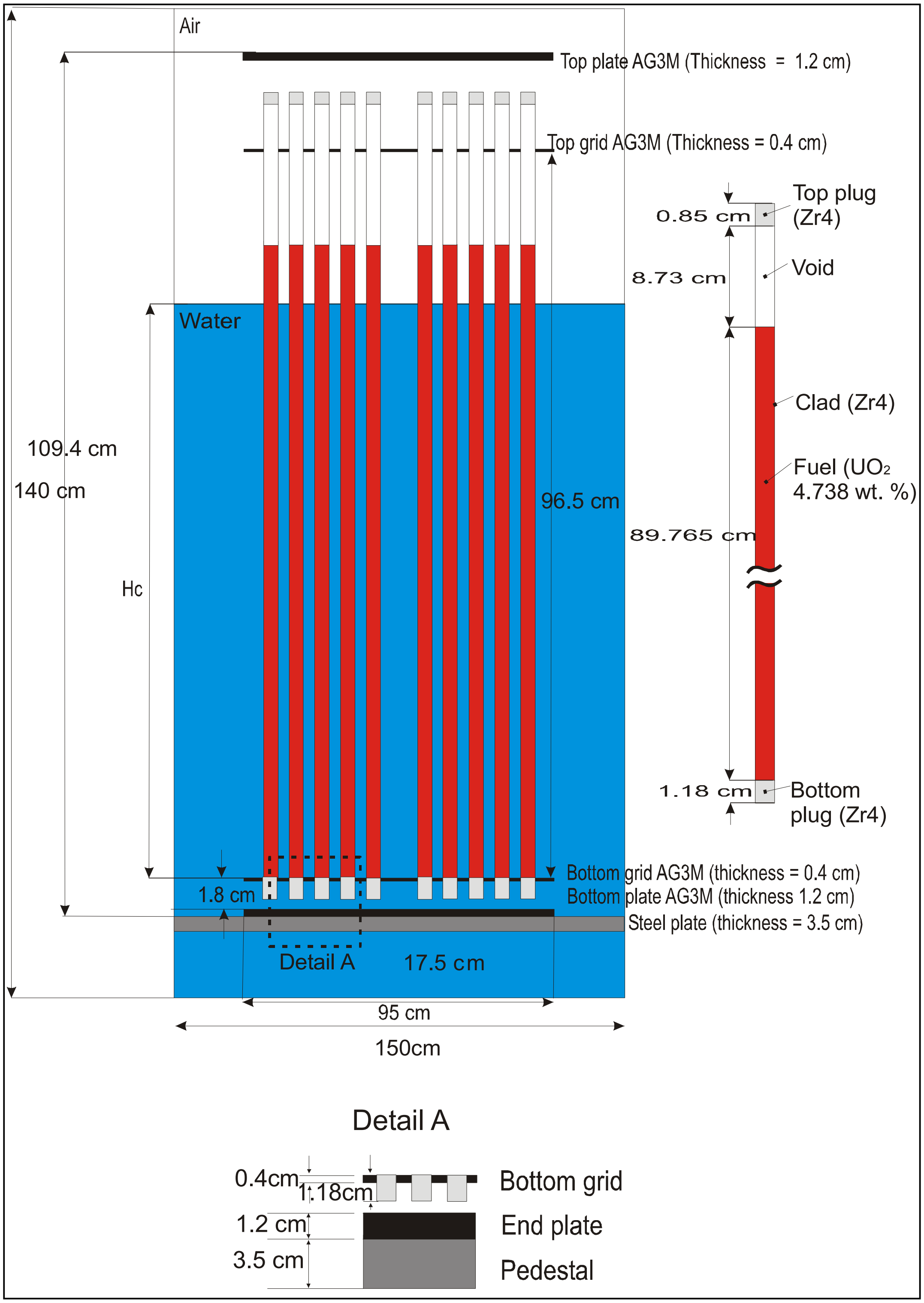
Due to the large amount of water (more than 20 cm) and the low reactivity effect of the emerged rods, the concrete room, and the steel tank walls may all be omitted.

The rod springs are not considered because they are not significant in terms of reactivity. Moreover, the rod plugs were replaced by cylinder-shaped plugs for calculations (1.18-cm-high cylinder for bottom plugs and 0.85-cm-high cylinder for top plugs).

The benchmark model geometry is shown in Fig. 4.

Five zones of small reactivity worth (top plug in void, clad and upper grid in void, clad in void, bottom plug in water, bottom plug and lower grid in water) could be described with homogenized materials according to the weighted volume fractions in APOLLO2-MORET4 route.

Figure 4 : Benchmark description – elevation view



3.2 Calculation results

Results obtained with the two calculation routes of CRISTAL package are presented in Tab. 5 and 6.

Table 5 : CRISTAL V1.0 calculation results for regular lattices

Configurations	Case number	Lattice pitch (cm)	Along Edge	Reflector	APOLLO2-MORET 4 k_{eff} +/- 0.00030 (1 σ)	TRIPOLI 4 k_{eff} +/- 0.00050 (1 σ)
Water-moderated and water-reflected tightly packed lattices	1	1.1	36 x 35	Water	0.99667	0.99683
	2	1.1	33 x 33	Water	0.99632	0.99723
	3	1.1	32 x 32	Water	0.99530	0.99633
	4	1.075	35 x 35	Water	0.99519	0.99659
Water-moderated lattices with a water or a CH_2 reflector	1	1.6	17 x 17	Water	1.00248	0.99969
	2	1.6	16 x 16	Water	1.00151	0.99880
	3	1.6	16 x 17	Water	1.00249	0.99928
	4	1.6	17 x 17	CH_2	1.00371	1.00069
	5	1.6	16 x 16	CH_2	1.00185	0.99860
	6	1.6	16 x 17	CH_2	1.00240	0.99875
	7	1.1	33 x 33	CH_2	0.99643	0.99747
	8	1.1	32 x 32	CH_2	0.99564	0.99638
	9	1.075	35 x35	CH_2	0.99523	0.99677

The first trends of this validation work point out a relative good agreement between the pointwise and the multi-group routes, allowing to conclude that the approximations used in the standard route are relevant for these kind of configurations.

Regarding, the calculation-experiments comparison, a small under-prediction (less than 0.5 %) has been highlighted for under-moderated lattices (corresponding to pitches ranging from 1.075 to 1.1 cm), whereas for well-thermalised ones (corresponding to pitches of 1.6 cm) a good agreement is observed.

Finally, no visible trend has been noticed with the CH_2 reflector, whatever the pitch of interest. Thus one can conclude about the accuracy of the CH_2 cross sections in thermal and epithermal energy range for such kind of configurations.

Table 6 : CRISTAL V1.0 calculation results for lattices with water cross

Case number	Lattice pitch (cm)	Configuration	APOLLO2-MORET 4 k_{eff} +/- 0.00030 (1 σ)	TRIPOLI 4 k_{eff} +/- 0.00050 (1 σ)
1	1.05	Assemblies with 6 rods removed separated by 2 pitches	0.99665	0.99477
2	1.05		0.99670	0.99497
3	1.05		0.99524	0.99445
4	1.075	Assemblies separated by 1 pitch	0.99970	0.99807
5	1.075		0.99764	0.99685
6	1.075	Assemblies with 6 rods removed separated by 1 pitch	0.99835	0.99638
7	1.075		0.99802	0.99677
8	1.075		0.99608	0.99463
9	1.075	Assemblies separated by 2 pitches	0.99989	0.99733
10	1.075		0.99948	0.99577
11	1.075		0.99887	0.99596
12	1.075	Assemblies with 15 rods removed separated by 2 pitches	0.99707	0.99589
13	1.075		0.99704	0.99467
14	1.075		0.99692	0.99487

Once again, calculation results in Tab 6 highlighted a relative good agreement between TRIPOLI4 and APOLLO2-MORET4 (average discrepancy between the two calculations routes is about 0.2 %) and a small under-prediction of k_{eff} because of small pitches involved.

4. Conclusion

This paper presents critical experiments dealing with low-enriched UO_2 “tightly packed lattices”. These configurations were performed with different square pitches (1.05, 1.075cm, 1.1 cm and 1.6 cm) corresponding to a range of EALF values from 0.106 to 0.899 eV.

Three main configurations were studied: water-moderated and water-reflected tightly packed lattices, CH_2 reflected water-moderated lattices and water-moderated lattices with water holes.

The first set of experiments intends to contribute to the criticality codes validation for low-moderated UO_2 arrays, the second set allows CH_2 cross section validation in thermal and epithermal range and the last one could be useful for the validation of BWR lattices.

All these 27 experiments have been investigated with CRISTAL V1.0 safety package. Main results highlighted a small under-prediction of less than 0.5 % for experiments with lattices pitches ranging from 1.05 to 1.1 cm, whereas for lattices with higher pitches a good agreement was obtained. Comparisons between the reference route and the standard route of CRISTAL, using JEF2.2 nuclear data, shown that the trends observed are not code dependent. Moreover, no visible trend has been noticed with the CH_2 reflector, allowing being confident about the accuracy of the CH_2 cross-sections in thermal and epithermal energy range.

Finally, this validation work is still in progress. The effect of different nuclear data libraries (JEFF3.1 and ENDF/B-VI) will be studied in order to have more information about ^{235}U and ^{238}U nuclear data accuracy in thermal and epithermal energy range.

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