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High Moderation Boiling Water Reactors fully loaded with MOX fuel : The BASALA Experimental Program.

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ABSTRACT

This paper is devoted to the BASALA experimental program launched in the EOLE facility in CEA-Cadarache within the framework of a cooperation between the CEA, COGEMA and the Japanese organization NUPEC. This programme, performed between 2000 and 2002, was aimed at investigating the physical phenomena occurring in High Moderation Boiling Water Reactors fully loaded with MOX fuel. The first configurations (BASALA-H) were dedicated to simulate hot operating conditions by adjusting the moderation ratio and the second configurations (BASALA-C) to simulate further high moderation conditions than BASALA-H and corresponding to cold. One year was devoted for the experimental study for each phase in which reference and perturbed (2×8 and 2×16 Gd rods, voided and higher moderated cores, absorbing control blades) configurations were investigated. In addition integral soluble boron efficiency up to 600 ppm and the isothermal temperature coefficient up to 80°C were measured in the BASALA-C reference core. The first section presents the experimental programme and the main results. One shows that the experimental data were obtained with a very good accuracy, compatible with the required uncertainty to validate calculation tools for High Moderation BWR design. The second part describes the main calculation/experiment results obtained by CEA and NUPEC : the calculation reproduce rather well the experiment (i.e. the fission rate is given within ±1.5% discrepancy in average).

1. Introduction

In 1995, the French "Atomic Energy Commission" (CEA) and the Japanese governmental agency "NUclear Power Engineering Corporation" (NUPEC) launched a collaboration focussed on MOX recycling in advanced LWRs. After having investigated the neutronic parameters of MOX-fuelled PWRs in the MISTRAL [1,2,3,4] programme, the cooperation was extended in 1999 to the high moderated Boiling Water Reactors (BWR) loaded with 100% MOX through the BASALA Programme [5,6].

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This program, implemented in the EOLE facility of the CEA-Cadarache from 1999 to 2002, was specially designed to be representative of such BWR loaded with 9x9 MOX fuel assemblies. It was shared in two phases : the BASALA-H and BASALA-C cores devoted to simulate hot and cold BWRs conditions respectively. The first section describes the experimental programme and the second chapter gives an overview of the experimental results. The CEA and NUPEC calculation tools are shown in the third paragraph and the last section is devoted to the main calculation/experiment comparisons.

2. The BASALA Programme

During the BASALA programme, two phases were investigated :

- The BASALA-H phase was aimed at simulating hot conditions of high moderation BWR with moderation ratio (H/HM - hydrogen to heavy metal atomic ratio of ~5) : the rod pitch was 11.3 mm and the assembly pitch was 114.1 mm. The four central test bundles, loaded with four Pu-content fuel pins varying between 3.0% and 8.7%, were surrounded by a driver zone containing 12 ABWR assemblies loaded with MOX-7.0% fuel pins (Figure 1). The critical size was obtained by adding MOX-4.3%, MOX-8.7% pins. For the cores involving heterogeneities, enriched UO_2-3.7% pins were used to reach the criticality. Figure 2 shows the reference core of BASALA-H
- The BASALA-C was dedicated to simulate further higher moderation conditions up to H/HM ~ 9 and cold conditions of BWR : the rod pitch and assembly were 13.5 mm and 135.5 mm respectively. This core was specially dedicated to investigate the reactivity margins : the reactivity effects of absorber control blades (metallic Hf and natural B_4C pellets) were thus measured and were completed by the measurement of the integral soluble boron efficiency up to 600 ppm. Figure 3 reproduces the critical core configuration obtained for the B_4C control blade study.

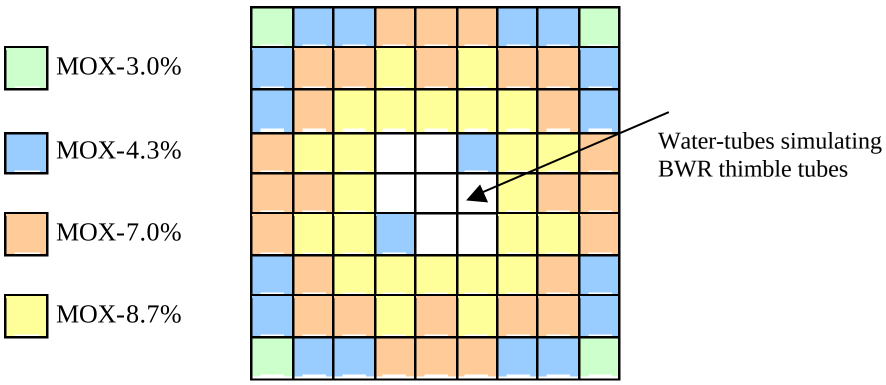

Fig. 1 Loading pattern of the Central test ABWR sub-assembly

In BASALA-H, a core was specially designed for simulating a high void fraction (~70%) when using thick overclads for the central MOX fuel pins. In parallel, the higher moderated core was obtained by replacing 8 MOX fuel pins by water tubes in each central subassembly enabling an increase of the water quantity in the BWR test assemblies. In both BASALA-H and BASALA-C, a specific study was performed for evaluating the effects of UO_2-Gd_2O_3 poison rods (enriched UO_2 ~5.0% of ^{235}U and ~2.5% of Gd_2O_3) : two configurations involving 2×8 and 2×16 UO_2-Gd_2O_3 rods respectively were investigated.

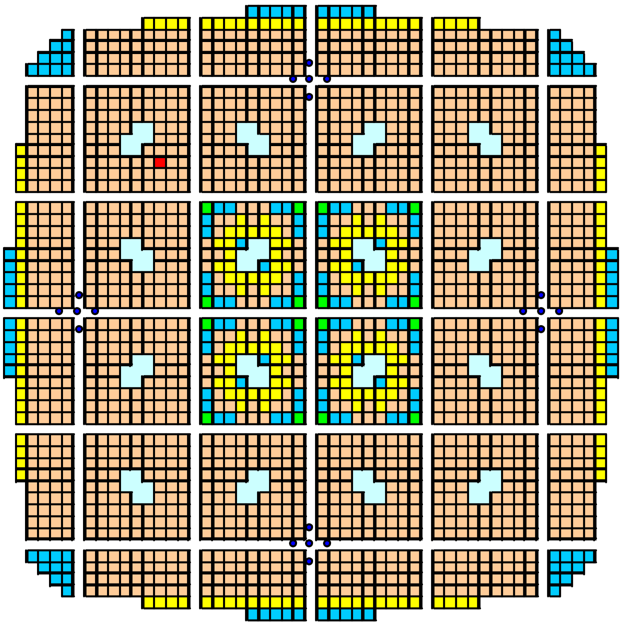

Fig. 2 The BASALA-H/REF core

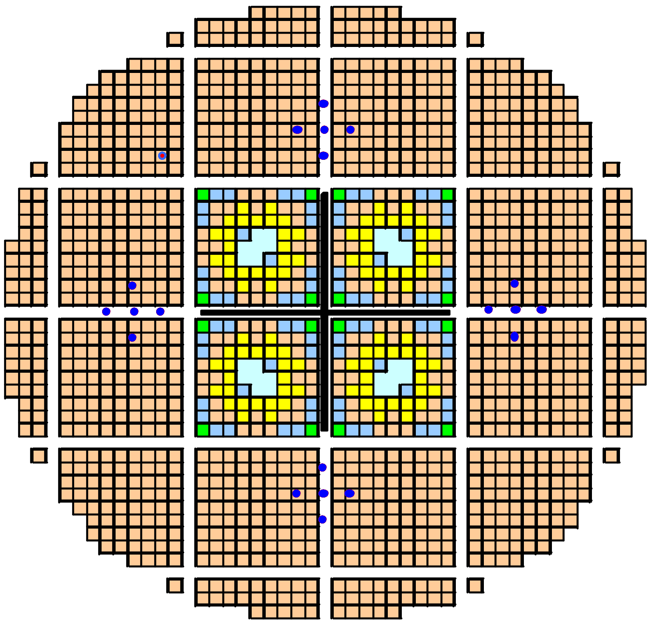

Fig. 3 The BASALA-C/B4C core

Legend

MOX-3.0%
MOX-4.3%
Safety Cluster – Enr. B_4C
MOX-7.0%
MOX-8.7%
Pilot Rod – Nat. B_4C

Furthermore, in BASALA-C, a cruciform hole was performed in the grids for enabling the insertion of ABWR-type control blades : the first one contained 2 metallic Hf sheets per aisle and the second was filled with 16 natural B_4C rods per aisle. For each configuration, the critical sizes were obtained by modifying the number of driver pins at the periphery of the core. The measured parameters are summarized in the table 1.

Table 1 Measured parameters in BASALA

Measurement	***BASALA-H***	***BASALA-C***
H/HM	~ 5	~ 9
Critical Mass	O	O
Boron Concentration	0 ppm	0 ppm
Radial power map	O	O
Axial power map	O	O
Integral Boron worth	-	O
Control Blade study	-	O (× 2)
Poison rod study	O (×2)	O (× 2)
Temperature study	-	O
2D-void study	O	-
Higher moderation core	O	-

3. Experimental Results

During the experimental program, and in addition to reactivity measurements performed by divergence and sub-critical measurement techniques, a special care was taken to obtain radial pin-by-pin fission rate distributions for reference cores and heterogeneity cores (8 and 16 UO_2-GdO_2 rods, voided condition simulation and additional water rods, inserting control blade) using integral γ-spectrometry directly on the pins. Thus more than one hundred fuel pins per configuration were investigated allowing the definition of almost complete sets of radial fission rate maps against which the computational tools used for high moderation BWR design were tested. The main measured reactivity are summarized in table 2.

Table 2 Reactivity effects of the investigated heterogeneities.

Phase	Core	Number of Additional pins	Δρ ($)
BASALA-H	VOID	+ 268 UO2	-3.54 ± 0.19
	8GD	+ 412 UO2	-5.49 ± 0.30
	16GD	+ 444 UO2	-5.92 ± 0.32
	High moderated core	- 188 MOX	+ 2.10 ± 0.11
BASALA-C	8GD	+ 345 MOX	-11.44 ± 0.69
	16GD	+ 404 MOX	-15.61 ± 0.94
	Hf Control Blade	+ 584 MOX	-26.92 ± 1.62
	B_4C Control Blade	+ 600 MOX	-28.28 ± 1.70

This table indicates that :

- The simulation of voided situation leads to a negative effect and the introduction of additional water tubes in the test assemblies (over-moderated core) gives a positive effect due to higher moderation.
- The 8 UO_2-Gd_2O_3 rods have almost same efficiency as the 16 rods in both cores, because of the location of the rods in the 8Gd configurations. Their individual effect is higher because most of Gd rods are located near the water-gap increasing the thermal neutron flux and consequently their anti-reactivity : for example we have $\Delta\rho(_{UO2\text{-}Gd203})^{8Gd}$ = -0.34±0.02$/rod and $\Delta\rho(_{UO2\text{-}Gd203})^{16Gd}$ = -0.19±0.01$/rod in BASALA-H.
- The Hf control blade gives almost same effect as the natural B_4C (density ~70%) but slightly lower.

The pin-by-pin fission rates were obtained within ± 1.5% S.D. in BASALA-H and ± 1.1%S.D. in BASALA-C. The difference seems to come from some bowing of the investigated MOX fuel pins and also from some dissymmetry in the mini-grid lattice pitch. These phenomena induces local moderation ratio variations which lead to perturb the local delivered power. Figure 4 shows a typical radial fission rate distribution measured along a diagonal in BASALA-C reference core.

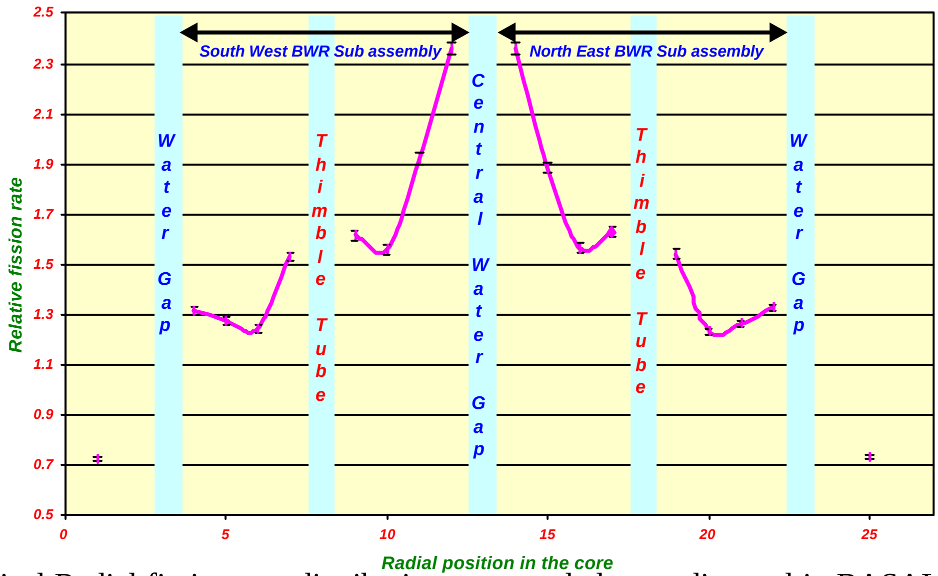

Fig. 4 Typical Radial fission rate distribution measured along a diagonal in BASALA-C/REF core

The comparison of BASALA-H and BASALA-C references cores shows that each pins seems having the same behavior : the maximum and the minimum powers are obtained for the same pin (located in the corner of the test assembly). The same kind of effect can be observed when comparing the power maps obtained in the cores containing the heterogeneities (table 3).

Table 3 Synthesis of the global perturbations due to heterogeneities in the BASALA Programme

Phase	Heterogeneity	Range of variation	Maximum Discrep.	Location of Max.	Minimum Discrep.	Location of Min.
BASALA -H	High Mod.	+6%/+74%	+74%	(33.34) MOX-8.7%	+6%	(31.31) MOX-3.0%
	VOID	-18%/-34%	-34%	(36.36) MOX-4.3%	-18%	(32.31) MOX-4.3%
	8Gd	-14%/-35%	-35%	(32.32) MOX-7.0%	-14%	(34.33) MOX-8.7%
	16Gd	-7%/-34%	-34%	(37.37) MOX-7.0%	-7%	(31.31) MOX-3.0%
BASALA -C	8Gd	-8%/-29%	-29%	(22.22) MOX-7.0%	-8%	(26.21) MOX-8.7%
	16Gd	-5%/-31%	-31%	(27.27) MOX-7.0%	-5%	(21.21) MOX-3.0%
	Hf	-2%/-81%	-81%	(29.29) MOX-3.0%	-2%	(21.21) MOX-3.0%
	B4C	0%/-82%	-82%	(29.29) MOX-3.0%	0%	(21.21) MOX-3.0%

- The voided case globally shows the same behavior of each pin (in BASALA-H)
- The Gd poison rods lead to strongly decrease the power in their neighborhood (both for BASALA-H and C), the 16Gd effect being slightly higher than the 8Gd effect (-34%/-35% in BASALA-H and –29%/-31% in BASALA-C)
- The control blades generate a huge flux depression in the center of BASALA-C, the Hf control blade having smaller effect than the B_4C control blade, mainly because its efficiency is slightly smaller.

The integral boron efficiency was obtained by subcritical measurements for 4 concentrations varying from 150 ppm up to 600 ppm. The results indicate that soluble boron has a reactivity effect almost linear with the boron concentration (figure 5).

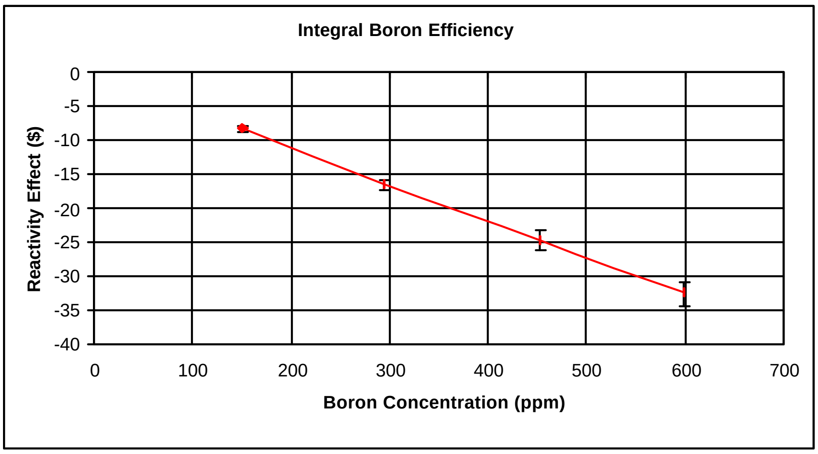

Fig. 5 Measured Integral Boron Efficiency in the BASALA-C/REF core in $

The isothermal temperature coefficient was investigated between 10°C and 80°C by divergence method and by subcritical measurements in the BASALA-C reference core with an uncertainty of ±2.0% in average. Figure 6 gives the measured ITC profile : because of a high moderated core (H/HM~9), the ITC is positive below 30°C and negative above.

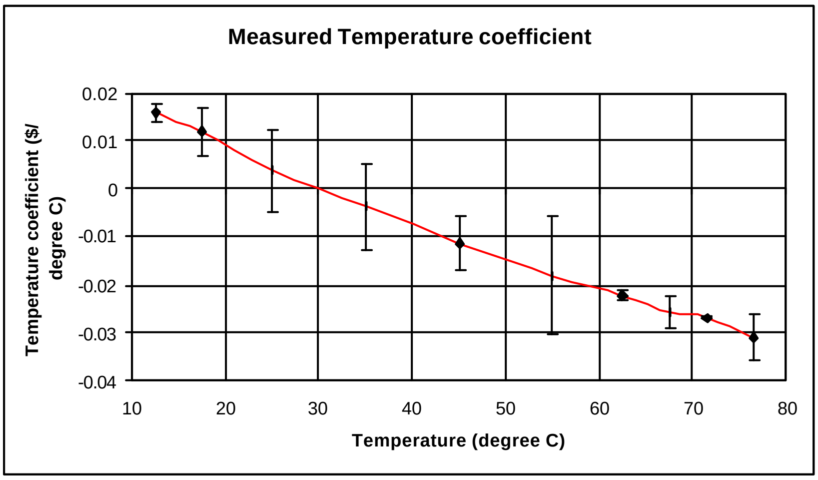

Fig. 6 Measured Isothermal Temperature Coefficient in the BASALA-C/REF core (in $/ degree C)

4. Calculations.

The whole experimental results were then separately analyzed by NUPEC and CEA using their own calculation tools. NUPEC and CEA used their continuous energy Monte-Carlo code called MVP [7] associated to the JENDL3.2 library [8] and TRIPOLI-4 [9] associated to the JEF2.2 library [11] respectively. Figure 7 gives an overview of the calculation tools of NUPEC and CEA.

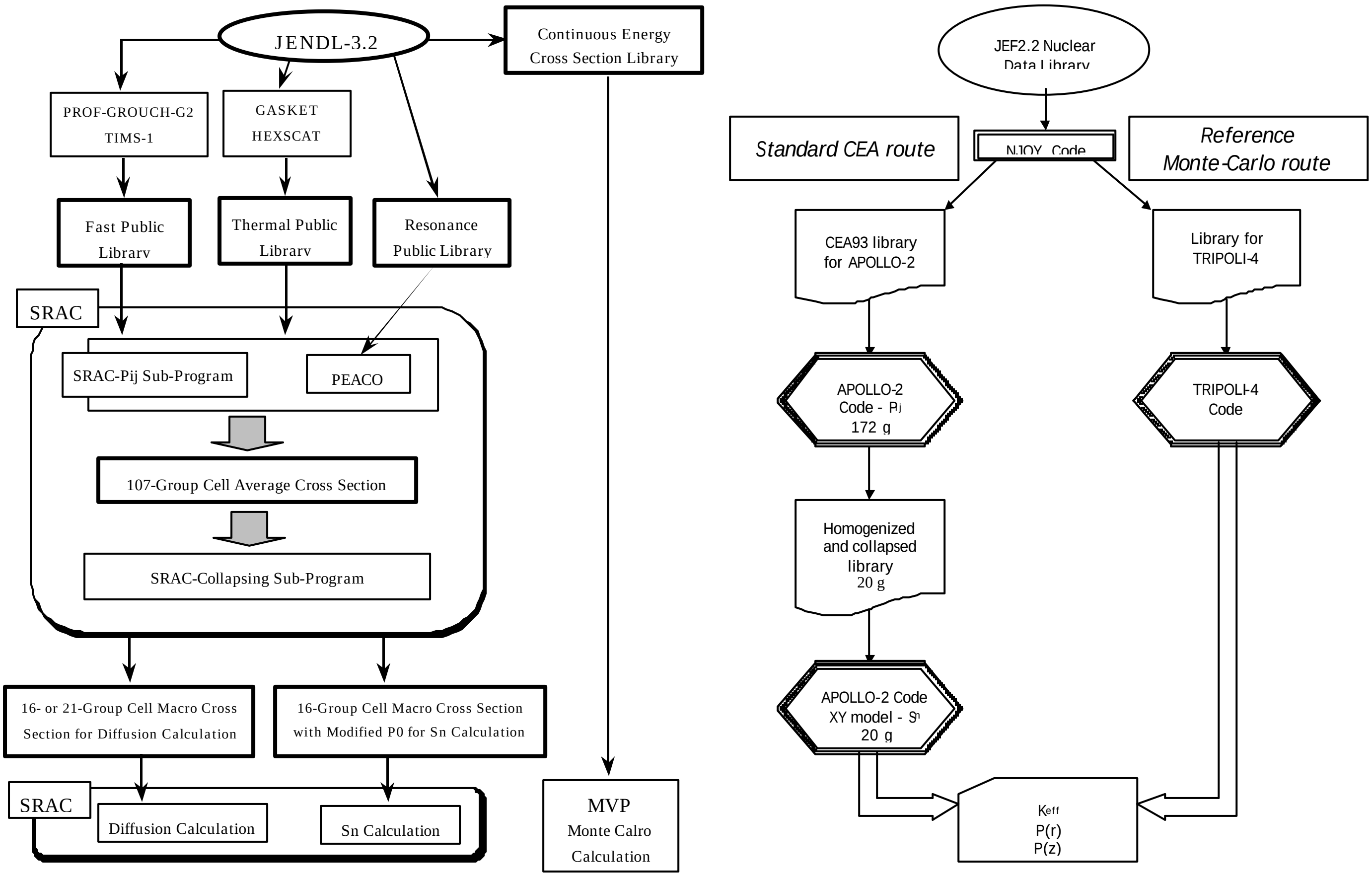

Fig. 7 Overview of the calculation schemes used by NUPEC and by CEA

The experimental/calculation comparison of the criticality is given in figure 8 (C-E in %dk) :

- The MVP code associated with the JENDL3.2 library overestimates the effective multiplication factors of +880±34 pcm in average for the whole considered cores, with +889±39 pcm for BASALA-H and +872±31 pcm for BASALA-C. No specific trend can be observed for the heterogeneities. The TRIPOLI-4 code with the JEF2.2 library overestimates the effective multiplication factors of +484±45 pcm for the whole considered cores. No specific trend can be observed for the Gd and Hf cores, a slight trend can be noted for the B_4C core for which the overestimation is slightly higher than for the other cores. The observed positive discrepancies come from the nuclear data which should be revised.
- CITATION reproduces rather well the reactivity of the BASALA cores with a discrepancy with MVP of about -540 pcm. For the transport solution, the discrepancy with MVP is much lower (about 200 pcm in average). The diffusion solutions are closer of the criticality than the transport solution, mainly because the P1 scattering effect is not correctly taken into account in the diffusion approximation. We note a rather large overestimation (~930 pcm) of the K_{eff} in BASALA-C/16Gd by the TWOTRAN code which is not consistent with the BASALA-H/16Gd Calculation/Experiment comparison.

More details about the calculations are given in reference [11].

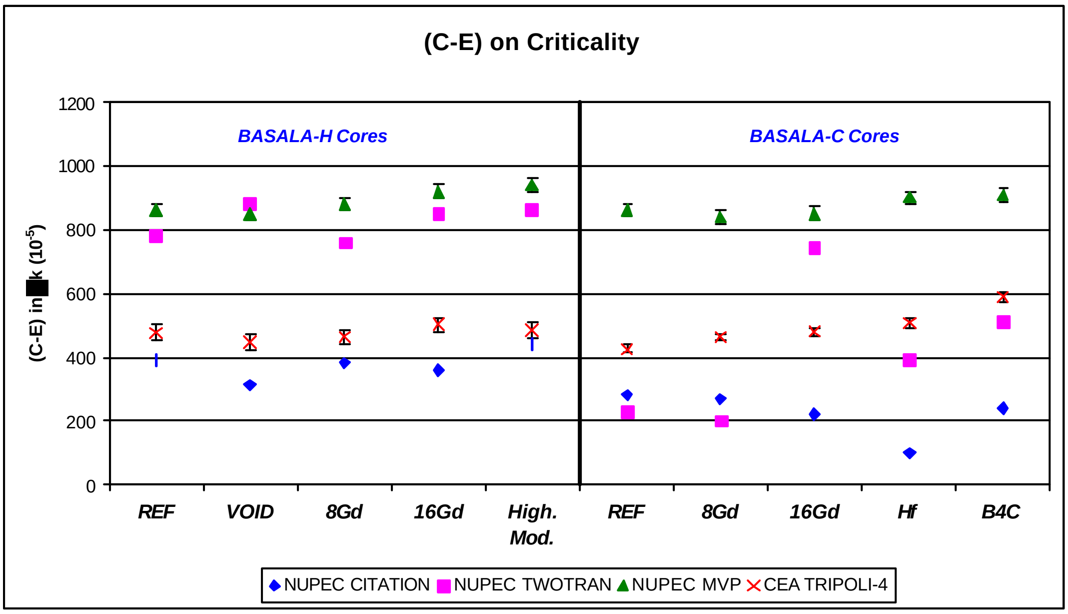

Fig. 8 (C-E) on criticality in 10^{-5} Δk.

These results allowed to evaluate the capability of the codes to reproduce the heterogeneity efficiencies. The Monte-Carlo codes give very accurate results [11] (except for MVP in the higher moderated BASALA-H core), for which the (C-E)/E are varying between -1.2% up to +2.4%, the experimental uncertainty being ±5.4% or 6.0% (1 S.D.). For the deterministic codes, one noted higher errors specially for CITATION in the VOID configuration (+6.4±5.4%) or TWOTRAN in the 16Gd core of the BASALA-C phase(-9.6±6.0%).

Figure 9 gives an example of (C-E)/E in % obtained for radial power distribution in BASALA-C/REF core with the Monte-Carlo calculations. Table 4 synthesizes the observed discrepancies for the whole investigated and calculated configurations : the codes are able to reproduce rather well the fission rate distributions consistently with the experimental uncertainties. For example the MVP and TRIPOLI-4 codes give the fission rate within a ±1.4 % and ±1.2% error in average, while CITATION has some difficulties to correctly reproduce the power in the fuel pins neighbouring the control blade (the maximum error is -7.3% and -6.1% for B_4C and Hf control blade respectively).

CEA – TRIPOLI-4 + JEF2.2								
								0.4
							0.2	-1.1
						-0.8	1.1	1.1
					0.8	0.2	1.2	1.3
				Water tubes		-2.1	1.3	1.4
			0.8			0.0	-0.1	1.5
		-0.4	-0.4	-0.2	0.3	-0.3	0.4	0.1
	-0.3	0.4	-2.0	0.9	-0.4	0.2	-0.2	-0.2
1.5	-0.9	1.3	0.8	0.9	-1.0	0.6	-1.0	1.5
Root Mean Square ± 0.9% Maximum discrepancy = -2.1%								

NUPEC – MVP + JENDL3.2								
								0.9
							1.4	0.2
						-0.2	-0.9	0.2
					1.4	0.4	-0.1	1.2
				Water tubes		0.9	0.5	-0.3
			0.7			0.5	-1.1	1.0
		-2.2	1.4	0.5	0.6	-0.6	0.2	0.4
	-1.1	0.5	-1.1	-0.9	0.4	0.4	-1.8	0.1
-0.8	-0.7	-0.9	-0.6	-0.6	-0.3	-0.5	-0.1	0.4
Root Mean Square. ± 1.0% Maximum discrepancy = -2.2%								

Fig. 9 (C-E)/E in % related to fission rate distribution in the central assembly of BASALA-C/REF for NUPEC and CEA (Normalized as Average [C-E]/E = 0%)

Table 4 Synthesis of (C-E)/E for radial power distributions.

Synt. parameter / Calculation	Exp. Unc (%	Maximum difference (%)				Root-mean square error %			
		CIT.	TWO.	MVP	TRIP.	CIT.	TWO.	MVP	TRIP.
BASALA-H/REF	1.7	-4.1	+3.9	-4.1	-2.5	1.8	1.4	1.5	1.1
BASALA-H/VOID	1.4	+4.1	+5.4	+3.6	-4.0	1.8	2.4	1.4	1.3
BASALA-H/8Gd	1.7	+4.6	+5.3	+3.9	+4.0	1.7	1.9	1.4	1.2
BASALA-H/16Gd	1.2	-3.8	-5.7	-3.2	+3.2	1.4	2.2	1.2	1.1
BASALA-H/GT	1.7	-4.0	+4.0	+3.9	-3.7	1.7	1.8	1.5	1.3
BASALA-C/REF	1.1	-2.9	+3.2	-2.2	-2.1	1.0	1.6	1.0	0.9
BASALA-C/8Gd	1.4	-3.7	+5.0	+3.4	-2.7	1.5	1.8	1.4	1.3
BASALA-C/16Gd	1.7	+4.1	+5.1	-3.4	+2.0	1.5	2.7	1.3	1.2
BASALA-C/Hf	1.4	-7.3	-4.0	+2.9	-3.1	2.0	1.4	1.3	1.2
BASALA-C/B4C	1.4	-6.1	+3.6	+4.4	-2.5	1.8	1.3	1.6	1.1
Average (a)		**4.5**	**4.5**	**3.5**	**3.0**	**1.6**	**1.9**	**1.4(b)**	**1.2(b)**

(a) Average of absolute values for the maximum difference.

(b) Uncertainty on computed reaction rate by Monte-Carlo code is ± 1.5%

The positive temperature coefficient below 30°C is well reproduced by the MVP code, the other results being satisfactory accounting for the accuracy of the Monte-Carlo code on the multiplication factor. A more detailed calculation using deterministic transport code seems to be required to confirm these results. The integral boron efficiency was calculated by NUPEC (MVP+JENDL-3.2): it is reproduced within ±5±6% (1 S.D.) discrepancy range.

5. Conclusions.

The BASALA program was launched in the EOLE facility in order to provide NUPEC and CEA with a valuable experimental data base for the validation of codes used for the high moderation MOX BWR design. Ten specific and representative configurations were thus implemented, in which the criticality and radial fission rate distributions were studied. Thus more than 1200 MOX pins were measured by integral γ-spectrometry allowing to obtain a very large data base with a very good accuracy : the fission rates were measured within ±1.5% and ±1.1% (1.S.D.) in BASALA-H and BASALA-C cores respectively. “Safety” parameters were also investigated in BASALA-C in order to meet the reactivity margin requirements : the integral boron efficiency and the cruciform control blade effects were obtained with a rather small uncertainty. The calculations were performed by Monte-Carlo and deterministic codes of NUPEC and CEA. The results indicate a rather satisfactory calculation of the criticality : a slight over-prediction was found certainly due to the used nuclear data ; the TRIPOLI-4 and MVP codes show an error of +480±45 pcm and

+840±34 in average. The radial rate distributions are very well reproduced by the Monte-Carlo codes but “high-efficient” heterogeneities lead to underestimate (down to ~ -7%) the power in the fuel pin neighboring the heterogeneity with deterministic codes. The positive ITC below 30°C and the integral boron efficiency are rather well reproduced by MVP. Further investigations are currently in progress in CEA with deterministic codes in order to evaluate their capability to design high moderated full-MOX BWRs.

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