ANALYSIS OF VOID EXPERIMENTS WITH A CONTINUOUS ENERGY, PROBABILISTIC METHODOLOGY

G.B. Bruna[1], C. Garat, C. Trakas, FRAMATOME,
Tour FRAMATOME, 92084 Paris la Défense

and

J. - L. Guillet and G. Rouvière, COGEMA,
1, rue des Hérons, 78182 St.-Quentin en Yvelynes

ABSTRACT

In the framework of a study on the feasibility of full Plutonium loading PWR cores, sponsored by COGEMA and currently carried out by FRAMATOME, a wide qualification of the Monte Carlo MCNP4 code with continuous-energy JEF2.2 library, in use at FRAMATOME for design and safety analysis, was undertaken. The qualification was also searched for intermediate and hard spectrum conditions, such as partial and full heterogeneous void. It was achieved both for reactivity and reaction rates on a 35-experiment basis including homogeneous and heterogeneous, Uranium, Plutonium and mixed fuel mock-ups. A wide selection of partial and full heterogeneous void configurations at 2 and 3D was included in the experimental basis for qualification. The paper shows that the MCNP4 code, with its reference JEF-2.2 library, is qualified for applications to very heterogeneous situations in space and energy, for all Plutonium enrichments and isotopic compositions in the design range.

1. FOREWORD

In the early 70s, Plutonium recycling was limited to fast reactors.

In France, commercial recycling Plutonium in Pressurized Water Reactors (PWRs), through Mixed Plutonium and Uranium OXide (MOX) fuel, began in the late eighties.

[1] Corresponding author and conference speaker

Today, recycling Plutonium through MOX fuel is a mature industry in the country, with a successful operational experience and large-scale manufacturing plants. As of first of June 1999, FRAGEMA, the joint venture of FRAMATOME and COGEMA, has delivered 1356 MOX fuel assemblies to 21 nuclear power plants in Europe (17 in France, 2 in Germany and 2 in Belgium) [REF. 1].

In France, since 1987, MOX fuel has been loaded in 17 reactors of 900 MWe PWR type, three more units have already been granted license for such fuel recycling and requests for eight additional units are pending.

Nowadays, COGEMA and FRAMATOME have undertaken a specific study-program on the feasibility of full MOX loading PWR cores. This program includes neutronic, thermal hydraulic, safety and system analysis [REFs. 2, 3].

2. COMPUTATION OF PLUTONIUM LATTICES

As far as nuclear data are concerned, Plutonium recycling in PWRs requires accurate evaluations for cross sections of Plutonium isotopes, including even ones (Pu^{38}, Pu^{40} and Pu^{42}) which contribute to the neutron absorption in the whole energy range and to fast fission, and for data of minor Actinides (mainly Am^{41} and Am^{43} and Cm), which are involved in power and temperature effects, participate significantly to reactivity change throughout the cycle and contribute to void reactivity change. Both capture and fission cross sections must be known accurately, mainly in the resonance range. Uranium data are also to be qualified carefully.

On a computational point of view, several specific developments and the qualification of computational tools on experimental basis are needed in order to develop new capacities and reduce overall uncertainty on computed integral parameters. E.g., evaluation of self–shielding and calculation of intra-pellet power distribution in cell codes must generally be improved according to an increased sensitivity of the effective cross sections to heterogeneity in space, distribution of neutrons in energy and temperature.

The modelling of the spectral transition between UOX / MOX regions is quite hard because of the huge differences in the average cross sections of the media. Local heterogeneities do not have any significant consequences on the overall reactivity balance of the system, but they do have an impact on the fine power distribution among pins, which limits operating performances via linear power and DNB. This phenomenon is widely increased when a MOX region, surrounded by UOX zones, is either partially or fully voided up.

The SCIENCE design code package developed and used by FRAMATOME for PWR neutronic design [REF. 4] has been fully qualified for partial Plutonium recycling via a large program including exploitation of operating experience, interpretation of selected mock-up experiments and analysis of MOX fuel pins irradiated in NPP units. Generalization to full MOX loading has recently been achieved in the framework of the above-mentioned program.

3. PHYSICS OF VOIDING IN PLUTONIUM LATTICES

Any partial or full voiding in a Plutonium fueled core generates a transient, the behaviour of which is roughly governed by the history of the reactivity change in time that determines the final conditions. The reactivity change depends, at any time, on the neutronic and the thermal-hydraulic features of the system. Simplifying, we can write:

$$dr(t)^{v} = dr(t)^{m} + dr(t)^{sb} + dr(t)^{c} \ ,$$

where:

$dr(t)^{v}$ is the reactivity of the system at time t,

$dr(t)^{m}$ accounts for the moderator effect,

$dr(t)^{sb}$ accounts for the direct and spectral effects of soluble boron,

$dr(t)^{c}$ accounts for overall feedback of the core.

Both $dr(t)^{sb}$ and $dr(t)^{c}$ depend on the reactor status. They are only indirectly related to void, while $dr(t)^{m}$, depends on the very nature of voiding (rate, geometry), fuel, lattice and core layout.

Generally speaking, two kinds of scenarios can occur:

> The homogeneous voiding, which accounts for all the situations in which the system is progressively voided in a roughly homogeneous way,
>
> The heterogeneous voiding, which accounts for all the widely theoretical situations in which, for a short period of time, void should be 'salt and pepper' distributed in the core, before reaching an homogeneous-like behaviour.

The physics of the homogeneous voiding without leakage in PWR lattices is a very well known matter today [REFs. 5 and 6]:

> Consequences of the spectrum hardening on the contribution of different reaction rates to reactivity have been fully explored, emphasising the fundamental role of the epi-thermal capture, fast fission and inelastic scattering of U^{38}, epi-thermal capture and fast fission of even Plutonium isotopes, fission of U^{35} and odd Plutonium isotopes, and contributions from minor actinides and poisons,

Sensitivity of the reactivity to void rate, Plutonium enrichment, poisoning and fuel composition has been widely analyzed,

The impact of these phenomena has been fully appraised to update computational chains and to define ad hoc mock-up experiments for qualification.

The matter is quite different as regards partial heterogeneous voiding, the study of which was first performed in a code benchmark perspective in [REF. 7].

Physics of partial voiding is quite complex because it relies on two antagonistic phenomena:

The absolute reactivity change of the voided region (which, in a first approximation, behaves roughly as if it were in infinite medium),

The change of coupling between the wet region and the zones drying away, which depends on the void rate, location and size.

Any local voiding renders the interested zone more and more permeable to fast neutrons, which are able to cross it in a growing number, without being trapped in the fuel resonances, which are mainly located in the 1 ev – 200 ev range. These neutrons strengthen the coupling among the surrounding regions, which remain moderated, so that the asymptotic contribution of the voided region to the chain reaction drops out progressively.

The overall reactivity change of the system comes about as the net effect of the contrasting infinite-medium and coupling contributions: whichever dominates, the reactivity follows.

Moreover, in heterogeneous voiding conditions, wet regions are the source of fast (from fission) as well as epi-thermal and thermal neutrons (from scattering and slowing-down). When crossing voided region, low energy neutrons are absorbed in a quite thin layer beyond the boundary and intermediate energy ones are progressively slowed-down, mainly by inelastic scattering on U^{38} and Oxygen, to resonance region where they are finally absorbed. Neutron spectrum hardens up quite slightly when moving toward the centre of the voided region and asymptotic infinite medium conditions, if any, can only be reached in the very central part of the sample.

According to the features described here above, calculations of such heterogeneous-void situations must be performed with a continuous energy probabilistic code, able to cope with the huge spectrum transition between flooded and voided regions. Thus, studies in FRAMATOME are performed with the Monte – Carlo code MCNP4 [REF. 8] using base data from the updated JEF-2.2 library [REF. 9]. In the framework of qualification, several experimental configurations were also interpreted with ENDFB-VI [REF. 9], for the sake of comparison.

4. DESCRIPTION OF THE JOB

4.1 FOREWORD

As said previously, heterogeneous void configurations were added to the experimental basis in the framework of the qualification of the MCNP4 code for design and safety studies of Plutonium fueled cores, currently carried out by FRAMATOME with the support of COGEMA.

More than design features (geometry, enrichment, coolant to fuel ratio), a qualification basis must account for fundamental parameters as either the neutron balance or the reaction-rates of the isotopes relevant to the phenomena of interest. These parameters measure the representativeness of the mock-ups against core conditions [REF. 10].

Individual sensitivities are rich in information, but their number could be very high and their calculation could show-up very impractical so that spectrum indexes were chosen as main indicators, as representative of the physical reaction rates (U^{38} Capt/ Pu^{39}Fiss; U^{38}Fiss/ Pu^{39}Fiss; Pu^{39}Fiss /U^{35}Fiss) relevant to voiding in MOX and heterogeneous UOX – MOX media.

4.2 SELECTION OF THE EXPERIMENTS

The available basis for qualification contains 195 critical mock-up experiments, 125 of which are fueled with UOX fuel, 70 with MOX, and 21 are heterogeneous, containing a mixture of UOX and MOX fuel (including ERASME [REF. 11] and EPICURE [REF. 12], carried out in the CEA EOLE facility at Cadarache, South of France).

To guarantee the qualification of the reaction rates of all relevant isotopes in all the energy regions spanned by the neutron spectrum in the voided conditions, we included in the 35-element basis two series of experiments devoted to Uranium and Plutonium qualification, respectively:

For Uranium:

a) GODIVA (5 very high-enrichment (95%) UOX spherical configurations [REF. 13]),
b) Low moderation ratio UOX mock-ups (4 configurations [REF. 13]),
c) Low-enrichment, heterogeneous UOX / UOX EPICURE UH 1.2 mock-ups (3 partially voided out of 4 configurations, [REF. 12], see Fig. 1),

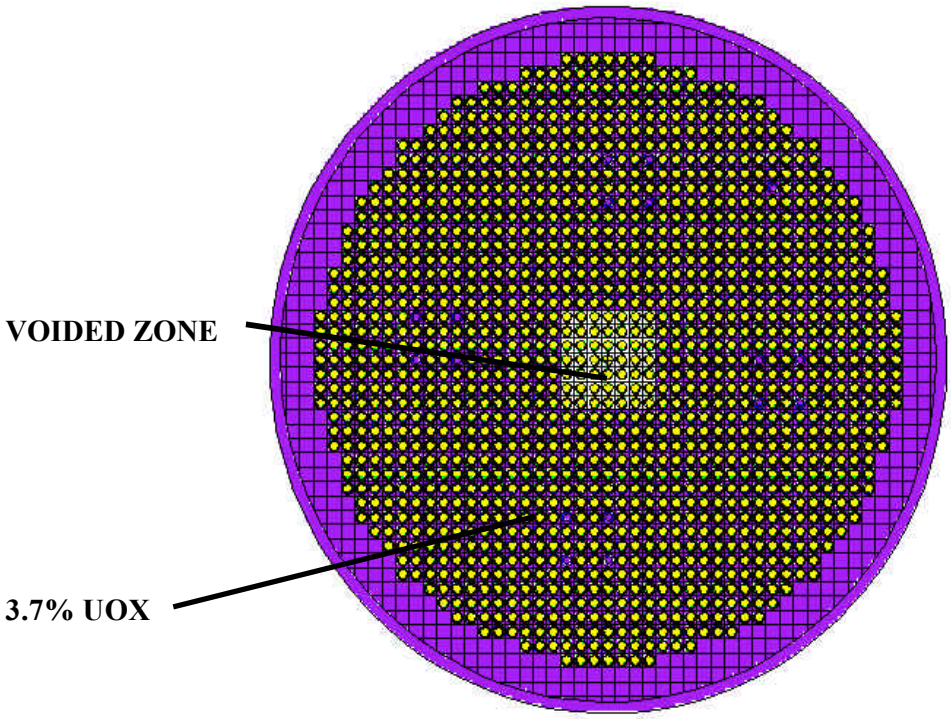

Fig. 1 Low enrichment, heterogeneous UOX/UOX EPICURE UH 1.2 mock-up experiment with partial void.

For Uranium and / or Plutonium:

d) JEZEBEL (4 very high-enrichment, pure PU^{39} and one very high-enrichment, 20% PU^{40} spherical configurations [REF. 12]),
e) ERASME S & R (4 tight-pitch high-enrichment hexagonal-lattice mock-ups [REF. 10]),
f) ERASME-L (3 square-lattice mock-ups, representative of the Plutonium recycling conditions in PWRs [REF. 10]),
g) EPICURE (3 MOX, low-enrichment (7% Pu), heterogeneous 2D configurations, 2 out of 3 with partial voiding [REF. 11]),
h) EPICURE (5 MOX, low-enrichment (7% Pu), heterogeneous 3D configurations, 4 out of 5 with one or more bubble voiding [REF. 11], see Fig. 2),
i) EPICURE (2 MOX, high-enrichment (11% Pu), heterogeneous 3D configurations, one out of 2 with big-size bubble voiding [REF. 11], see Fig. 2).

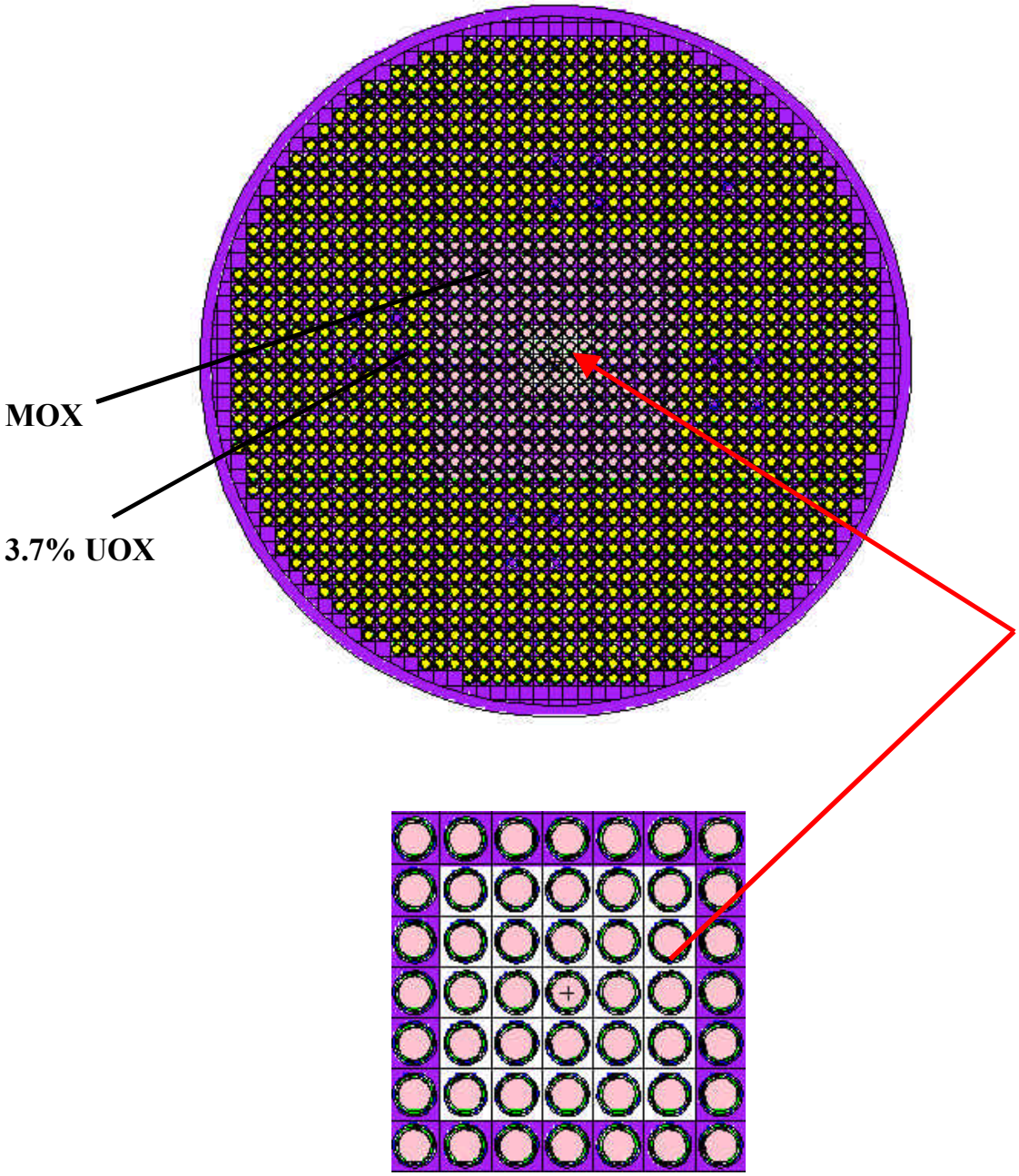

Fig. 2 Low and High enrichment, heterogeneous UOX – MOX EPICURE UM 17*17, MOX mock-up experiment with central bubble(s).

4.3 CALCULATIONS

Interpretation of all experimental configurations belonging to the qualification basis defined here above was performed with the MCNP4 continuous energy 3D Monte Carlo code developed at Los Alamos National Laboratory (USA) and currently in use at FRAMATOME for criticality and fundamental analysis.

The code can be run at FRAMATOME with both JEF2.2 and ENDFB-IV libraries at three different temperatures. Libraries are continuous in energy with 2000 to 300 000 points between 14 Mev and 0 ev, depending on isotope features (resonance abundance strongly increases the number of energy points).

Calculations were performed on a SPARK workstation, with very satisfactory results as regards both computational precision and running time. A typical EPICURE configuration with a full-void zone was converged in about 15 hours with a precision of ± 40 pcm (1 pcm = $1.0\ 10^{-5}$) at $1s$ on reactivity and $\pm 1\%$ on fission rate, while a one-bubble heterogeneous void configuration required about 60 hours to reach a statistical precision of about ± 20 pcm at $1s$ on reactivity and of about $\pm 2\%$ on point-wise reaction rates. These figures perfectly hit the objectives of qualification, and lay in the range of standard precision for such kind of measurements.

In order to achieve such very high convergence performances, 5 million histories and 30 million histories of neutrons were followed respectively in the EPICURE configurations mentioned here above, the geometry of which were laid out in a 1/16 representation with reflective conditions at the diagonal and median boundaries.

4.4 RESULTS

Validation of Uranium data

The qualification process entailed demonstration of the pertinence of the most relevant data of Uranium isotopes (U^{35}, U^{38}) followed by data of major (Pu^{39} and Pu^{40}) and minor Plutonium isotopes. Incidentally, qualification of moderator and structural materials was also achieved.

That way, GODIVA mock-ups (a) enabled to qualify U^{35} rates in the fast and epi-thermal domain and the low moderation ratio UOX mock-ups (b) enabled to qualify U^{38} cross sections in a whole, according to the large contribution of its rates to the overall neutron balance in these systems.

In the 4, low-enrichment, heterogeneous UOX / UOX EPICURE UH 1.2 mock-ups (c), void was simulated by replacement of the liquid moderator by a solid aluminium alloy in a 7*7 central lattice 80 cm high (see Fig. 1 for geometry details).

Reactivity and pin-wise reaction rates in the experimental zone have been evaluated with a precision of ± 50 pcm and 1% at $1s$ respectively. Owing to the presence of aluminium and the size of the voided region, spectrum in this mock-up is epi-thermal. Calculation results lay within the experimental uncertainty both for reactivity and reaction rates.

Table 1 shows a synopsis of the results of reactivity analysis.

[In this table and in the following ones, the SSI (Simplified Spectrum Index) is defined as the ratio of neutrons belonging to fast and epi-thermal regions over the thermal neutrons:

$$SSI = \frac{\int_{0.625}^{\infty} j\,dE}{\int_{0}^{0.625} j\,dE}].$$

CONFIGURATION	**KEFF**	**SSI INDEX in the 7*7 pin sample**	**Measured void effect**	**Computed void effect (MCNP4/JEF2.2)**
UH1.2	1.0016	7.5	_	_
UH1.2 30% void	1.0004	< 20	-543 ±50	-660 ±80
UH1.2 50% void	1.0005	< 20	-1111 ±50	-1220 ±80
UH1.2 100% void	1.0000	20	-2165 ±50	-2330 ±80
AVERAGE	1.0006		-1273 ±50	-1403 ±80

Tab. 1 Synopsis of void effect calculations in EPICURE UH.2 UOX – UOX configurations [pcm values (1 pcm = 1. 10^{-5})].

Fig. 2 shows the percent discrepancies between computed and measured fission rates in the above mentioned heterogeneous UOX/UOX EPICURE UH 1.2 mock-up with a 100% void in the central 7*7 pin region.

	20	21	22	23	24	25	26	27	28
28									
27								0.5	
26							1.0		
25						-1.2			
24					-1.2	-0.9			
23				-0.8	-4.5	-0.5			
22			1.2	-0.1	-3.1	-0.2			
21		1.1	1.0	0.5	-2.6	1.9	-1.3		
20	1.3	1.4	2.3	0.4	-0.8	2.9	1.3	0.6	

Fig. 3 Percent discrepancies in fission rate distribution in UH1.2 EPICURE configuration with a 100% central 7*7 pin-zone void. [In this and in the following figures, the (20,20) pin position indicates the core centre].

Results of these experiments allowed direct cross-section validation of Uranium isotopes and indirect cross-section validation of aluminium and zirconium, which contribute to the overall rate balance of the voided region up to 10% and 2%, respectively.

Data belonging to both JEF2.2 and ENDFB-IV libraries gave approximately equivalent results for these lattices.

Validation of Plutonium data

The fast domain of the main Plutonium isotopes (Pu^{39} and Pu^{40}) was explored via the interpretation of fundamental JEZEBEL (d) experiments, three out of which were fueled with roughly pure Pu^{39} and one contained up to 20% Pu^{40}. In the fast region of the spectrum, reactivity was slightly underestimated by MCNP4 calculations [450 pcm with JEF 2.2 library and 320 pcm with ENDFB-VI library on the average], but according to physical statements here above, this range contributes only slightly to the reactivity.

ERASME series mock-ups (e & f) are much more representative of the actual isotopic composition of a RG (Reactor Grade) Plutonium and the heterogeneous voiding conditions, each configuration showing the average behaviour of a zone in the transition from wet to dried regions. Table 2 (1 & 2) summarizes the main results of the analysis.

Generally speaking, these experiments give a satisfactory validation to both U^{38} and Plutonium data in the epi-thermal and the resonance regions.

1) CONFIGURATION	MODERATION RATIO	SSI INDEX (Fuel)	MCNP4 JEF2.2	MCNP4 BVI
PU 11% ERASME S Hexagonal	0.5	235	1.0042	1.0123
PU 11% ERASME R Hex.	0.9	100	1.0032	1.0065
PU 11% ERASME R Hex. SBC = 1150 ppm	0.9	106	1.0060	_
PU 11% ERASME R Hex. SBC = 2490 ppm	0.9	110	1.0030	1.0077
AVERAGE	_	_	1.0041	1.0088

2) CONFIGURATION				
PU 11% ERASME LP Sqrd	2.1	30	1.0020	0.9994
PU 11% ERASME LG Sqrd	2.1	< 40	1.0032	1.0032
PU 11% ERASME LG Sqrd Control Rods	2.1	< 40	1.0039	1.0026
AVERAGE	_	_	1.0030	1.0017

Tab. 2 Synopsis of ERASME-experiment interpretation results on reactivity (experimental value of Keff = 1.0000 ±50 pcm, 1 pcm = 1. 10^{-5}; 1 ppm = 1.10^{-6}).

Computations with ENDFB-VI library overestimate the reactivity of about 500 pcm on the average (but approximately 1000 pcm pick) in the tight-pitch lattices (ERASME S & R) and of only 200 pcm in the over-moderated ERASME-L (coolant to fuel ratio of 2.1) . Whenever the spectrum hardens-up in Plutonium lattices, an increasing overestimation of reactivity by ENDFB-VI has been observed, as a general trend throughout the whole study.

EPICURE experiments (g to i) include a series of heterogeneous MOX / MOX configurations fueled with RG Plutonium from a 33 000 MWd/tonne UO2 PWR cycle at 7 and 11% enrichment:

In the 3 low-enrichment 2D configurations, void ranges from 0 to 30% and 50% in a 7*7 pin zone of the central assembly,

In the basic low-enrichment 3D configurations (see Fig. 2 for geometrical features), voided region is smaller in radial size (a cube of only 6.5*6.5*10 cm 100% void, a "bubble"). A central bubble and a 30 cm displaced bubble configuration are at disposal,

Two more configurations exist in which the central voided region was increased by piling-up three and five voided bubbles,

In the high-enrichment 3D configuration, bubble is placed in the centre of the core.

CONFIGURATION	KEFF	SSI INDEX in the Voided Zone	Measured Effect	Computed Effect (MCNP4/JEF2.2)
UM 17x17 MOX 7% Reference	0.9986	30	0	0
UM 17x17 MOX 7% Central Bubble	0.9977 (1)	< 80	-103 ±8	-90 ±40
UM 17x17 MOX 7% Bubble at +30 cm	0.9986 (1)	< 80	-40 ±8	0 ±40
UM 17x17 MOX 7% 3 Piled-up Bubbles	0.9961 (1)	< 80	-230 ±8	-250 ±40
UM 17x17 MOX 17x17 5 Piled-up Bubbles	0.9957 (1)	< 80	-282 ±8	-290 ±40
UM 17x17 MOX 11% Reference	1.0007	40	0	0
UM 17x17 MOX 11% Central Bubble	0.9991 (1)	< 150	-130 ±16	-160 ±40
AVERAGE VOID EFFECT		_	-157 ±10	-158 ±40

(1) Reference Soluble Boron Concentration (SBC).

Tab. 3 Synopsis of EPICURE UM 17*17 reactivity analysis (pcm values).

As shown in Tab. 3, results of the interpretation of all these experiments are very satisfactory for reactivity, computed values being very close to the measured ones (with a statistical precision of MCNP4 / JEF-2.2 calculation of ± 40 pcm at $2s$). Very good results were also obtained when comparing pin power distributions of configurations belonging to (g) and (h) series, with average discrepancies lower than $\pm 2\%$, which represents both the experimental and computational uncertainty. Observed trend was maintained when using ENDFB-VI base-data.

Interpretation of the fully 3D (i) series experiments with a confined full voided zone, gave far less satisfactory results on reaction rates. Discrepancies, which are up to 5% and more, [Figs 3

and 4], could probably been partially reduced improving the measurement procedure. Their systematic character could be explained by a normalization problem: a 2% shift on the normalization value (point [20, 20]) should re-establish a roughly correct statistics.

	20	21	22	23	24	25	26	27	28
28									-0.2
27								2.9	-0.2
26							-0.6	1.7	2.3
25						-2.9	-0.7	-1.4	-1.6
24					-2.7	-1.7	-2.6	-5.0	-3.1
23				-1.3					-3.1
22			0.0						-3.7
21		-2.5							
20	1.4								1.3

	20	21	22	23	24	25	26	27	28
28									-3.3
27								--3.0	-5.0
26							-2.5	-1.6	-4.6
25						0.2	-1.6	-0.3	-1.8
24					2.8	-0.7	-1.9	-3.9	-1.9
23				2.1	1.2	2.6	0.1	-1.5	-0.5
22			2.0	5.2	4.2	1.1	1.2	3.1	-1.6
21									
20									

Fig. 4 Percent discrepancies in pin power distribution in reference (wet) and central bubble (dry) conditions, EPICURE UM 17*17 MOX 7% enrichment mock-up experiment [see Fig. 2 for geometry details].

	20	21	22	23	24	25	26	27	28
28									2.0
27								-1.0	2.2
26							2.7	0.3	2.3
25						3.2	-1.0	-1.4	1.3
24					4.7	0.7	-2.9	1.7	0.0
23				-1.5					1.6
22			0.7						2.9
21		2.7							-3.7
20	0.0								0.9

	20	21	22	23	24	25	26	27	28
28									-7.0
27								--6.0	-6.2
26							-4.8	-6.0	-5.5
25						-2.7	-4.0	-7.0	-4.0
24					-0.8	-0.7	-1.8	-0.3	-1.6
23				-3.0	-2.1	-2.2	-0.7	0.0	-2.0
22			-2.8	-1.4	-2.3	-1.1	0.7	-1.5	-2.3
21		-0.4						-1.4	-4.3
20	0.0								-1.4

Fig. 5 Percent discrepancies in pin power distribution in reference (wet) and central bubble (dry) conditions, EPICURE UM 17*17 MOX 11% enrichment mock-up experiment [see Fig. 2 for geometry details].

Combined experimental and calculation analysis on these results is underway to have a deeper understanding and try to explain discrepancies: two investigation axes are being explored:

The sensitivity of experimental precision to the thickness of the measured layer,

The uncertainty of g scanning measurements, which is very sensitive to the very conditions of the measurement and to the yield data for fission produced in a very hard spectrum: without a suitable correction, discrepancies on the yield data can engender a several-percent uncertainty on fission reaction rates.

5. CONCLUSION

The paper shows that the MCNP4 code with JEF-2.2 continuous-energy library in use at FRAMATOME for criticality and safety studies is qualified for applications to very heterogeneous situations in space and energy, such as partial and full voids of core zones surrounded by wet regions, for all Plutonium enrichments and isotopic composition in the design range.

Discrepancies between measured and computed values of reactivity lay within a range of [-50 pcm, - +1310 pcm], on the bulk of 35 experiments, with an average at 40 pcm only. No significant trends and bias are observed between JEF-2.2 and ENDFB-VI results, except for very hard-spectrum asymptotic conditions where ENDFB-VI calculations systematically overestimates reactivity relative to JEF2.2 up to a maximum of 1000 pcm in quite extreme cases [Tab. 4].

CONFIGURATION	MODERATION RATIO	SSI INDEX	MCNP4 JEF2.2	MCNP4 BVI
GODIVA (5)	0	> 200	1.0003	0.9993
JEZEBEL (4)	0	> 360	0.9955	0.9968
ERASME (7)	0.5 à 2.1	>30 <235	1.0036	1.0053
URANIUM Low Coolant/Fuel Ratio (4)	0.27 à 0.78	>10 <80	1.0036	_
EPICURE (15)	1.2	>7 <150	0.9993	_
AVERAGE (35)			1.0004	

Tab. 4 Overall synopsis on reactivity calculations. Figures in () account for the number of experiments.

Pin-power distributions have also been analyzed on several experimental configurations of the EPICURE program both for UOX and MOX fuel. For the most configurations, discrepancies lay widely within the experimental uncertainty.

Interpretation of 3D MOX experiments, with a confined several inches full voided zone, gave less satisfactory results on reaction rates. Discrepancies were up to more than 5% for JEF2.2 data. These discrepancies could have been slightly reduced whether using ENDFB-VI cross-section library, but reactivity predictions should be downgraded. Normalization problems and an increased uncertainty of experimental techniques in such lattices could be evoked to explain these discrepancies partially, but a full analysis on the topic is still underway.

REFERENCES

1) J.L. Nigon, J.P. Marcon, "The French MOX Fuel Irradiation Experience: Present Status and Future Improvements", *Proceedings of the ICÔNE 7 Meeting*, Tokyo, Japan, April 1999;

2) G. Rouvière, G.B. Bruna, J.-L. Guillet, J. Pelet, " 1300 MWe PWR, a New Step in Full MOX Core Design", *Proceedings of the GLOBAL '99 Meeting*, Jackson Hole, USA, August – September, 1999;

3) G. Rouvière, G.B. Bruna, J.-L. Guillet, J. Pelet, "Toward Full MOX Core Design", *Proceeding of the TOPFUEL Meeting*, Avignon, France, September 1999;

4) P. Girieud, "SCIENCE: The New FRAMATOME 3D Nuclear Code Package for Safety Analysis" *Proceedings of the ENC'94 Meeting*, Lyon, France, October 1994;

5) G.B. Bruna, A. Santamarina, G. Garzenne "L'effet de vidange dans les cœurs contenant du Plutonium", *Proceedings of the SFEN Topical Meeting on Plutonium Recycling*, "Aval du Cycle : la Question du Plutonium", Paris, June, 4, 1998;

6) R. Böehme, H.D. Berger; R. Chawla, H. Hager, R. Seiler and T. Williams, "Neutron Balance Investigations for a High Enrichment MOX-LWR Lattice Under Normal and Voided Conditions", in Y. Ronen and E. Elias Eds., "Reactor Physics and Reactor Computations", *Proceedings of the International Conference on Reactor Physics and Reactor Computation*, Tel Aviv, January 23 - 26, 1994

7) NEA - OECD, *Physics of Plutonium Recycling*, Vol. 1-4, Paris, OECD Documents, 1995-1996;

8) J.S. Hendricks et al. "MCNP4B Monte Carlo N-Particle Transport Code System", RSICC Computer Code Collection, Radiation Safety Information Computational Centre, CCC-660, Oak Ridge National Laboratory, April 1997;

9) P.Oblozinsky and O. Schwerer, "Nuclear Data and Online Services" in P. Oblozinsky and A. Gandini Eds. The Abdus Salam Centre for Theoretical Physics, UNESCO, NEA, *Nuclear Reaction Data and Nuclear Reactors. Physics, Design and Safety*, World Scientific, Singapore, 1999;

10) J.C. Cabrillat, "Reactor Physics Critical Experiments: Design and Analysis", in P. Oblozinsky and A. Gandini Eds. The Abdus Salam Centre for Theoretical Physics, UNESCO, NEA, *Nuclear Reaction Data and Nuclear Reactors. Physics, Design and Safety*, World Scientific, Singapore, 1999;

11) J. Bergeron, M. Darrouzet, J.-M. Gomit, R. Lenain, J.-L. Nigon, L. Martin-Deidier, "The French Neutronic Program Addressing the Requirements of Future Pressurized Water Reactors", Nucl. Technol., **80**, 269, (1988);

12) J.-P. Chauvin, J.- C. Cabrillat, P. Fougeras, S. Cathalau, P.J. Finck, "EPICURE: Synthesis of an Experimental Program Devoted to the Validation of the Calculation Scheme for the Pressurized Water Reactor Recycling MOX", *Proceedings of the Physor '96 Meeting*, Mito, Japan, September 1996;

13) NEA – OECD, *International Handbook of Evaluation Criticality Safety Benchmark Experiments*, Rev. March 1995, Paris, 1995;

14) S. Cathalau, J.-P. Chauvin, P. Fougeras, A. Maghnouj, "Calculation of 2D and 3D Local Void Effects in MOX Reactors: Analysis of the EPICURE Results", *Proceedings of the Physor '96 Meeting*, Mito, Japan, September 1996.