Experimental critical loadings and control rod worths in LWR-PROTEUS configurations compared with MCNPX results

Michael Plaschy*[1], Michael Murphy[1], Fabian Jatuff[1], Rudolf Seiler[1], and Rakesh Chawla[1,2]
[1]*Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland*
[2]*École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne Switzerland*

Abstract

The PROTEUS research reactor at the Paul Scherrer Institute (PSI) has been operating since the sixties and has already permitted, due to its high flexibility, investigation of a large range of very different nuclear systems. Currently, the ongoing experimental programme is called LWR-PROTEUS. This programme was started in 1997 and concerns large-scale investigations of advanced light water reactors (LWR) fuels. Until now, the different LWR-PROTEUS phases have permitted to study more than fifteen different configurations, each of them having to be demonstrated to be operationally safe, in particular, for the Swiss safety authorities. In this context, recent developments of the PSI computer capabilities have made possible the use of full-scale 3D-heterogeneous MCNPX models to calculate accurately different safety related parameters (e.g. the critical driver loading and the shutdown rod worth). The current paper presents the MCNPX predictions of these operational characteristics for seven different LWR-PROTEUS configurations using a large number of nuclear data libraries. More specifically, this significant benchmarking exercise is based on the ENDF/B6v2, ENDF/B6v8, JEF2.2, JEFF3.0, JENDL3.2, and JENDL3.3 libraries. The results highlight certain library specific trends in the prediction of the multiplication factor k_{eff} (e.g. the systematically larger reactivity calculated with JEF2.2 and the smaller reactivity associated with JEFF3.0). They also confirm the satisfactory determination of reactivity variations by all calculational schemes, for instance, due to the introduction of a safety rod pair, these calculations having been compared with experiments.

KEYWORDS: LWR-PROTEUS configurations, research reactor operation, critical loading, reactivity worth, MCNPX, 3D-simulations

1. Introduction

The experimental programme LWR-PROTEUS [1] has permitted the detailed investigation of various light water reactor (LWR) configurations since 1997. A principal aim thereby has been the provision of an up-to-date integral database for the optimisation of boiling water reactor (BWR) assembly designs. In this context, the PROTEUS research reactor presents the advantage of one's being able to load nine full-length authentic fuel assemblies into its central test zone, rather than having to employ an experimental mockup. However, in order to make the system critical and have a relatively unperturbed neutron spectrum for the experimental investigations, PROTEUS is characterised by four separate regions (the central test zone, a surrounding buffer zone, an annular D_2O-driver region, and an external graphite driver/reflector region), each of which has a specific role (see Fig. 1). For instance, the external graphite zone contains the control rods, as also the shutdown/safety rods and the reactor

* Corresponding author, Tel. +41-56-310-2883, Fax. +41-56-310-4527, E-mail: michael.plaschy@psi.ch

instrumentation. Under these conditions, the use of a stochastic code like MCNPX [2], which makes accurate 3D-modelling feasible, is very beneficial. In the current analyses, the MCNPX capability to predict the critical loading, the reactivity worth of the shutdown rods and the reactivity excess (compensated by the control rods) is assessed for seven different LWR-PROTEUS configurations.

2. The experimental LWR-PROTEUS programme

The experimental LWR-PROTEUS programme consists of three different phases. Phase I has been devoted to the determination of power and ^{238}U capture rate distributions in Westinghouse SVEA96+ BWR fuel assemblies [3]. Phase II was related to the analysis of the reactivity effects associated with burnt samples introduced into a pressurised water reactor lattice [4]. Phase III concerns the investigation of modern BWR-type assemblies, and, in particular, the effects due to the presence of part-length pins [5]. For each phase, different configurations have been considered, modifying, for example, the axial location of the test zone and/or the moderation conditions. As indicated earlier, the uniqueness of the LWR-PROTEUS experiments is mainly related to the presence in the central test zone of entire advanced BWR-type assemblies of 4 metres length. However, the currently loaded configuration, Core III-4, has a mockup test zone representing a new and innovative LWR type, as described below. The configurations employed for the present critical loading and reactivity worth investigations are:

(a) Core I-1A
The test zone is characterised by 3x3 Westinghouse SVEA-96 BWR assemblies immersed in pure water.

(b) Core I-2A
The test zone is characterised by 3x3 Westinghouse SVEA-96 BWR assemblies and two absorbing hafnium wings immersed in pure water.

(c) Core I-3A
The test zone is characterised by 3x3 Westinghouse SVEA-96 BWR moderated by various polyethylene elements, no water being present in the test zone.

(d) Core III-1
The test zone is characterised by 3x3 Optima2 BWR assemblies immersed in a mixture of ~34% D_2O and ~66% H_2O.

(e) Core III-2
The test zone is characterised by 3x3 Optima 2 BWR assemblies immersed in the above mixture (~34% D_2O), the only change compared to Core III-1 being the axial location of the fuel assemblies.

(f) Core III-3
Again, the test zone is characterised by 3x3 Optima2 BWR assemblies immersed in the same D_2O/H_2O mixture. Compared to Cores III-1 and III-2, the changes are the axial location of the fuel assemblies and the presence of four sub-bundle boxes in the central assembly, which can be filled with different moderators.

(g) Core III-4
As mentioned earlier, this PROTEUS configuration corresponds to a completely different test zone. The 3x3 Optima2 BWR assemblies have been integrally removed and replaced by a square lattice of 5% ^{235}U enriched UO_2 fuel rods (the lattice being surrounded by a significant air zone, as presented through the corresponding MCNPX2.5 model, see Section 3). This innovative lattice has been loaded, on one hand, to permit the facility to be critical with the

PROTEUS own fuel (no more nuclear power plant assemblies used), and, on the other hand, to be representative of HPLWR (High Performance Light Water Reactor) assemblies [6].

The experimental loadings of Cores I-1A, I-2A, I-3A, III-1, III-2, III-3, and III-4, as well as the corresponding values of excess reactivity and shutdown rod worths, have been investigated. Since these seven configurations differ significantly in terms of the central test zone (fuel enrichment, moderation conditions, loading arrangement, etc.), the corresponding calculation/experiment comparisons are quite suitable for assessing the MCNPX capabilities to reproduce the neutronics of the highly heterogeneous, multi-zone PROTEUS facility. In particular, the analysis of excess reactivity and shutdown rod worths is directly associated with an appropriate evaluation of the neutron flux in the external graphite region, the control and shutdown rods being inserted in this zone. In this context, the experimental determination of the reactivity effects has been achieved using either standard rod-drop techniques or period measurements.

3. MCNPX modelling and simulations

All the calculations presented in this paper are based on MCNPX-2.5 simulations. The code offers the ability to model accurately highly heterogeneous lattices such as that of the SVEA-96 assembly. The current MCNPX-2.5 analysis has been carried out using the American nuclear data libraries ENDF/B6 (releases 2 and 8) [7], the European nuclear data libraries JEF2.2 and JEFF3.0 [8], and the Japanese nuclear data libraries JENDL3.2 and JENDL3.3 [9].

The MCNPX2.5 models developed are whole-reactor 3D models. These are based on previous studies [10], but various improvements have been incorporated to optimise the modelling [11] while reproducing the Phase III configurations. Fig. 2 shows, for example, a XY-cut at the core mid-plane of the Core I-1A model. The detailed consideration by the model of the four different zones of the PROTEUS facility is clearly highlighted, the positions of the 16 shutdown rods (borated steel) and the 4 control rods (elements comprising Cd-segments), for example, being considered explicitly.

The model for the test zone of each configuration studied is presented separately in order to further underline the high degree of detail (see Figs. 3-6; the choice of colours made by the stochastic code by default has been conserved). Thus, Fig. 3 highlights the specificity of Core I-2A, viz. the presence of two Hf-absorber blades between the 3x3 advanced BWR assemblies, while Fig. 4 indicates the location of the polyethylene rods present in Core I-3A. From the comparison of the test zone models for Cores III-1, III-2 and III-3 (see Figs. 4 and 5), the presence of four sub-bundle boxes in the central assembly in the case of Core III-3 (as described in Section 2) can be clearly seen. Finally, Fig. 6 presents the currently loaded, innovative HPLWR-type lattice.

The MCNPX2.5 simulations were all performed using the recently installed parallel processing system, MERLIN, at PSI, thus achieving the computational speed necessary for considering the detailed Monte Carlo modelling of the highly heterogeneous PROTEUS reactor.

4. Calculation/experiment comparisons

With the aim to validate the MCNPX-2.5 models for the prediction of the various LWR-PROTEUS safety parameters, systematic calculation/experiment comparisons have been made for the seven different reactor configurations described in Section 2. In the current analyses, assessment has been made, as indicated earlier, for the MCNPX prediction of (a) the critical loading, (b) the reactivity worth of the shutdown rods and (c) the reactivity excess (compensated by the control rods). It is worth noting that the reactivity effects are expressed in $ using a specific β_{eff} value for each configuration. This has been calculated with the help of a recently developed Monte Carlo procedure (see Tab. 1) [12].

4.1 Critical loading

A good prediction of the critical loading is essential to design optimally a new experimental configuration. The MCNPX2.5 results obtained for each configuration using the different nuclear data libraries are given in Tab. 2 and compared in Fig. 7. This benchmarking exercise highlights clearly the significant dependence of the prediction on the nuclear data employed. In particular, the systematically higher k_{eff} prediction obtained with JEF2.2 is obvious. On the contrary, JEFF3.0 leads to the lowest k_{eff} values, but the discrepancy is not as large as that with JEF2.2. Finally, for the four other nuclear data libraries used (ENDF/B6v2, ENDF/B6v8, JENDL3.2, and JENDL3.3) a reasonably small mutual deviation is observed (maximum spread of ~200pcm between these four different libraries).

Compared to the experimental value, k_{eff} =1.0 (±20pcm due to the "autorod" which is not modelled), the calculations performed with JENDL3.3 and JEFF3.0 are the most satisfactory (discrepancy always smaller than ~ 500pcm). It is also interesting to underline that the more problematic cores are Cores I-2A, I-3A, and III-3. These configurations are the most heterogeneous systems investigated with the presence of Hf-blades (I-2A), polyethylene pins (I-3A) and a central stainless steel box (III-3). On the contrary, the criticality of Core III-4 is particularly well calculated almost by all the calculational schemes, although this configuration presents an innovative inner fuel lattice with a large surrounding low-density region (particularly difficult to adequately model with deterministic codes).

4.2 Reactivity worth of the shutdown rods

The determination of the shutdown rods reactivity worth is given in Fig. 8. More precisely, the negative reactivity effect corresponds to the introduction of a single pair of shutdown rods (as done during the experiments). The experimental value varies from 0.85$ (±0.02) to 1.95$ (±0.02) between the seven configurations studied, indicating different neutron flux distributions in the reactor. This variation is very beneficial for validating the MCNPX2.5 calculations.

The results obtained are indeed satisfactory for all configurations and for each nuclear data library employed, the calculational values corresponding to the experiments within the uncertainties (see Fig. 8). Consequently, the prediction by MCNPX2.5 of relative large reactivity variations appears not to be problematic. This aspect makes the use of Monte Carlo ideal for the assessment of shutdown rod reactivity worths.

4.3 Reactivity excess

The reactivity excess, which is experimentally adjusted in function of the fuel loading in the graphite zone, corresponds to the reactivity effect due to the complete withdrawal of the four control rods from the critical state, leading to the most overcritical configuration. This excess reactivity is necessary to control the reactor and to reach the desired power level. In this study, the experimental value of the reactivity excess varied from 0.21$ (±0.03) to 0.29$ (±0.03) with respect to the investigated core.

The comparisons with the calculated reactivity excess values are given in Fig. 9. These comparisons are made difficult because of the large statistical uncertainties associated with the simulations. This reflects the known, and still current, difficulty of Monte Carlo methods to predict accurately small reactivity effects (unless very large computational times are considered). In this context, a detailed interpretation of the results is not appropriate. However, a satisfactory C/E agreement (within the uncertainties, although these are large) is generally observed for all configurations analysed, further investigations being indicated to be necessary in some cases.

5. Conclusions

This paper presents systematic comparisons between measured and calculated values of operational safety parameters resulting from the analysis of various LWR-PROTEUS configurations. The parameters studied are the critical loading, the reactivity worth of the shutdown rods and the excess (control-rod compensated) reactivity of the reactor. The experimental values have been deduced by applying rod-drop techniques and period measurements. The calculations have been performed with the stochastic code MCNPX in conjunction with different nuclear data libraries. The full-core 3D models employed represent significant improvements with respect to previous MCNP4B models of the PROTEUS reactor.

The results obtained are generally very satisfactory, indicating the benefit of using a Monte Carlo code to predict safety related parameters for heterogeneous reactor configurations.

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Table 1: Monte Carlo determination of β_{eff} for the various LWR-PROTEUS configurations studied [3]

Configuration	β_{eff} calculated value (pcm)	Configuration	β_{eff} calculated value
I-1A	731±3	III-1	728±3
I-2A	731±3	III-2	726±3
I-3A	727±3	III-3	729±3
		III-4	736±3

Table 2: Monte Carlo determination of the multiplication factor k_{eff} for the various configurations using different nuclear data libraries

Library	B6v2	B6v8	JEF2.2	JEFF3.0	JENDL3.2	JENDL3.3
k_{eff} (I-1A)	1.00083±18	1.00227±16	1.00468±20	0.99836±17	1.00195±18	1.00007±18
k_{eff} (I-2A)	1.00434±20	1.00572±16	1.00880±18	1.00277±15	1.00436±17	1.00353±18
k_{eff} (I-3A)	1.00684±12	1.00695±19	1.01184±20	1.00537±20	1.00645±19	1.00551±19
k_{eff} (III-1)	1.00096±10	1.00205±17	1.00591±16	0.99904±17	1.00211±20	1.00016±18
k_{eff} (III-2)	1.00174±10	1.00306±16	1.00677±16	0.99967±16	1.00278±17	1.00103±16
k_{eff} (III-3)	1.00308±10	1.00485±15	1.00867±17	1.00210±20	1.00397±17	1.00285±20
k_{eff} (III-4)	0.99956±6	1.00054±19	1.00304±18	0.99766±18	1.00027±19	0.99947±18

Figure 1: Schematic view of the PROTEUS facility indicating the four principal zones (test zone, buffer, D_2O driver, and graphite driver/reflector)

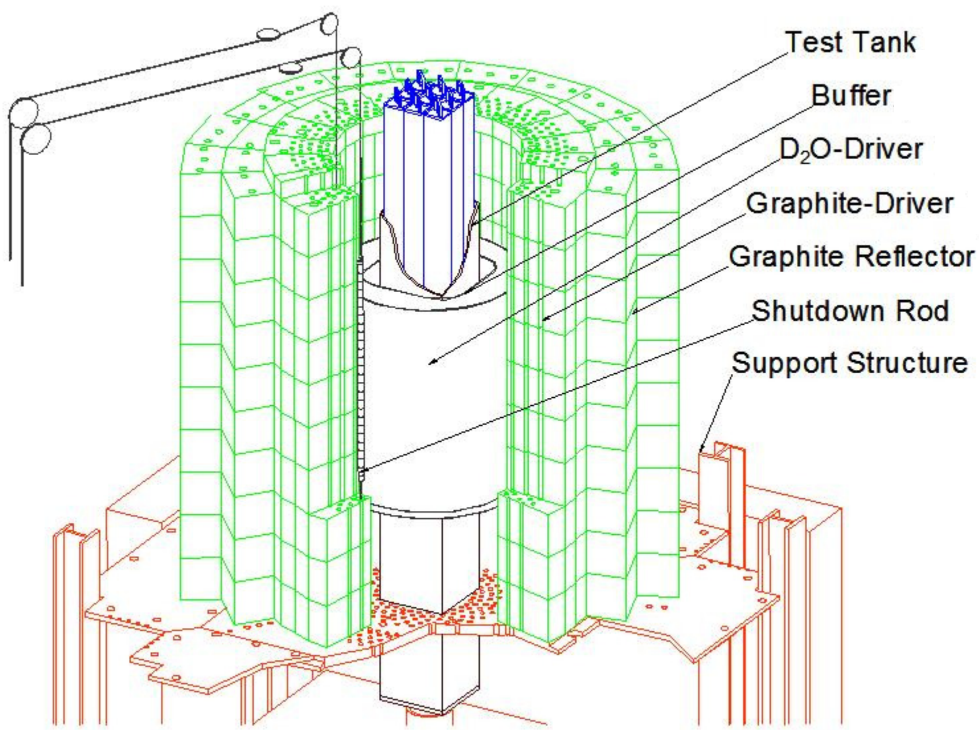

Figure 2: XY-cut of the MCNPX 3D-heterogeneous model of the configuration LWR-PROTEUS I-1A clearly showing the 4 different regions of the facility

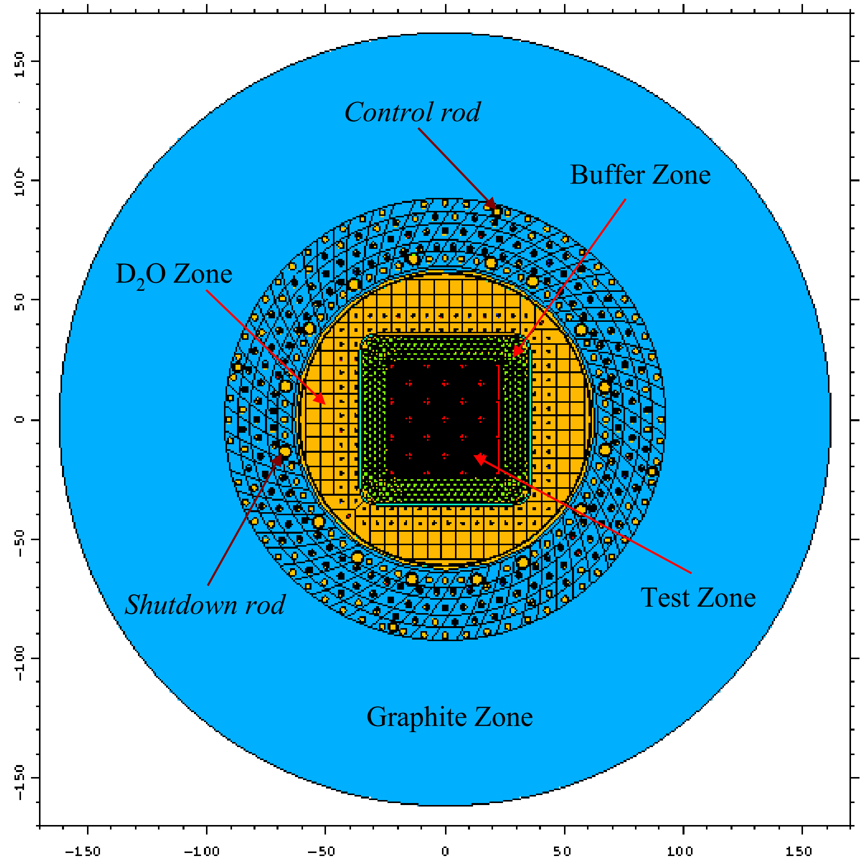

Figure 3: Zoom on the central test zone of the MCNPX 3D-heterogeneous models of the configurations LWR-PROTEUS I-1A (left) and I-2A (right)

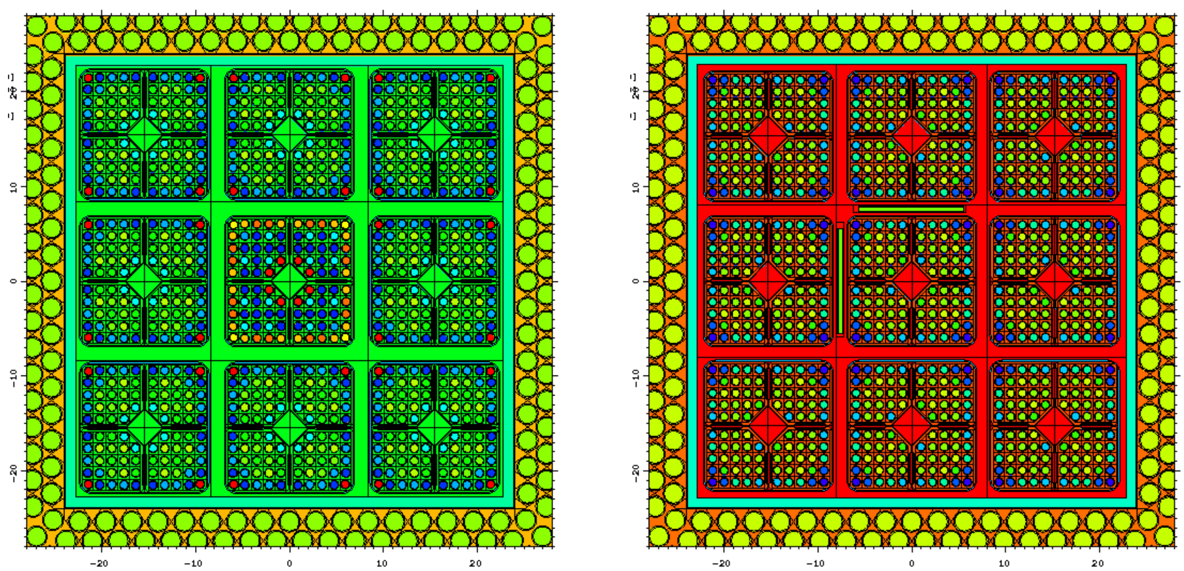

Figure 4: Zoom on the central test zone of the MCNPX 3D-heterogeneous models of the configurations LWR-PROTEUS I-3A (left) and III-1 (right)

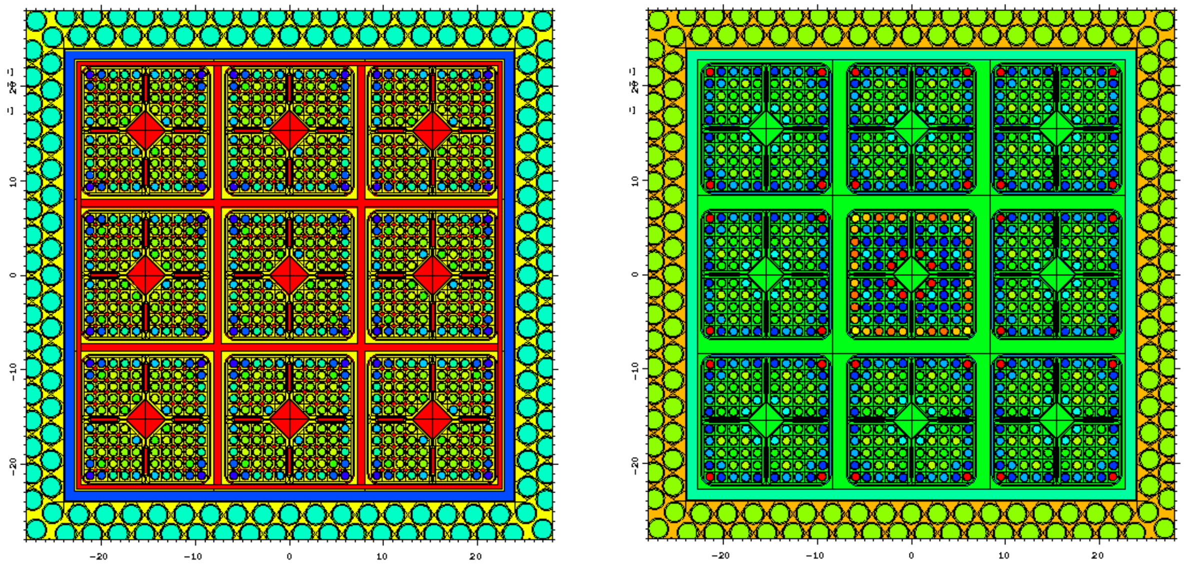

Figure 5: Zoom on the central test zone of the MCNPX 3D-heterogeneous models of the configurations LWR-PROTEUS III-2 (left) and III-3 (right)

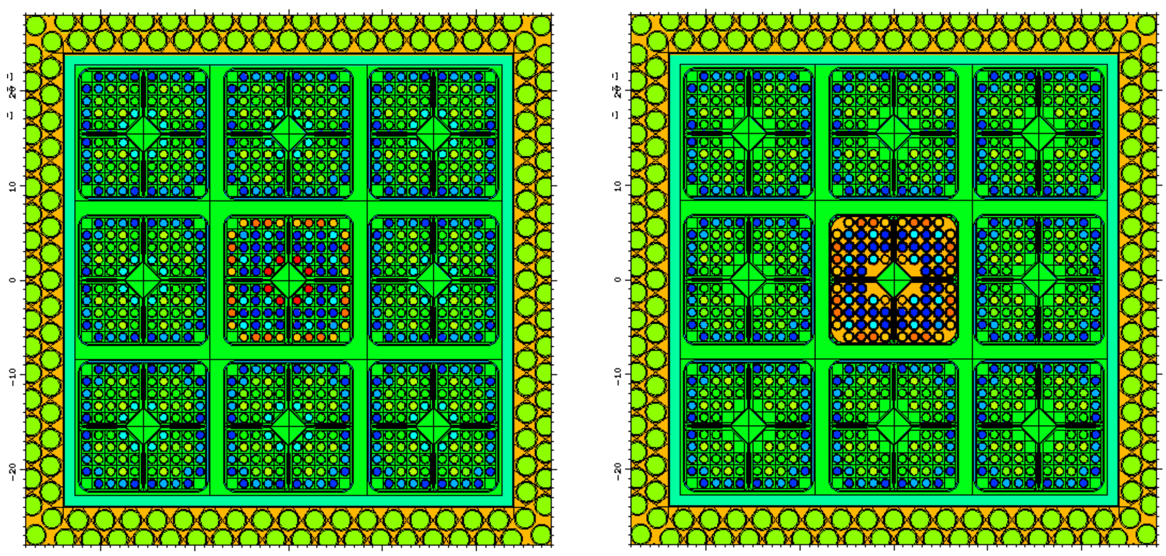

Figure 6: Zoom on the central test zone of MCNPX 3D-heterogeneous model of the configuration LWR-PROTEUS III-4, core currently loaded

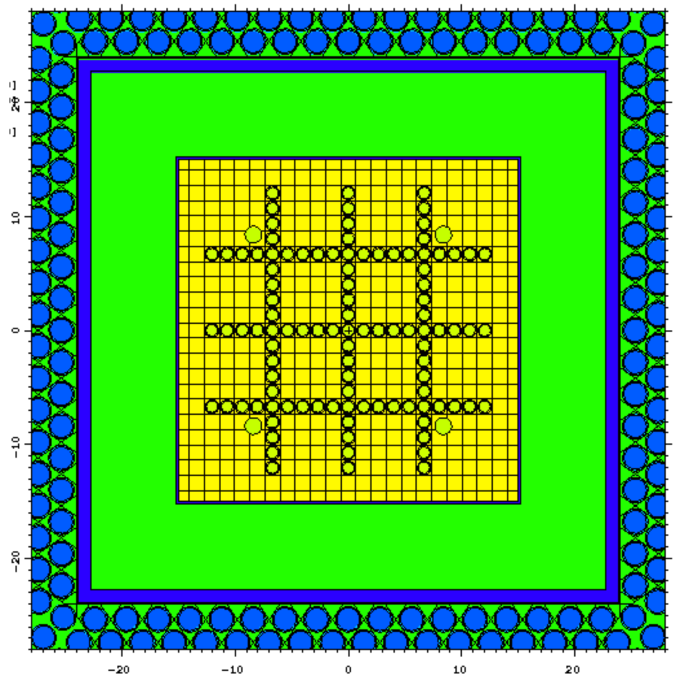

Figure 7: Monte Carlo determination of the multiplication factor k_{eff} for the various configurations using different nuclear data libraries (the experimental value being of course 1.0)

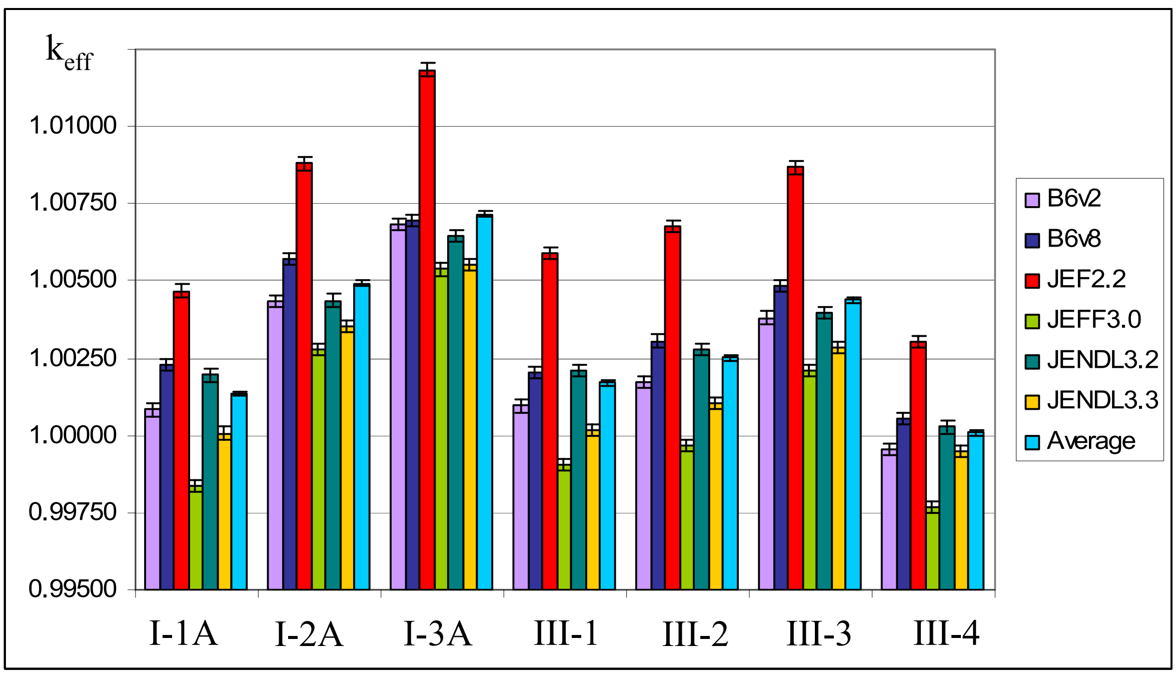

Figure 8: Monte Carlo determination of the reactivity variation (in $) due to the introduction of a safety rod pair for the various configurations using different nuclear data libraries, compared to the experimental value

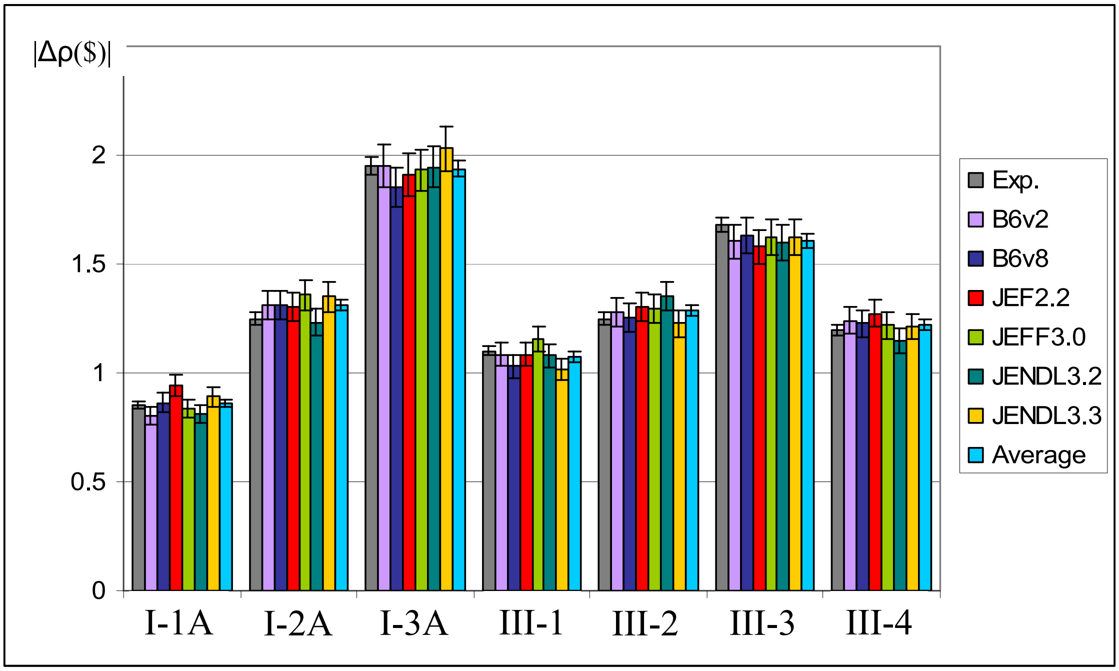

Figure 9: Monte Carlo determination of the maximum reserve of reactivity (in $) of the various configurations using different nuclear data libraries, compared to the experimental value