2013 International Nuclear Atlantic Conference - INAC 2013
Recife, PE, Brazil, November 24-29, 2013
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: **978-85-99141-05-2**

HEAVY STEEL REFLECTOR EVALUATION USING DIFFUSION THEORY

Pamela Piovezan[1], Alfredo Abe[2], Thiago Carluccio[1] and Adimir dos Santos[2]

[1] Departamento de Neutrônica e Blindagem – Centro Tecnológico da Marinha (CTMSP)
Av. Professor Lineu Prestes, 2468
05508-000 Cidade Universitária, SP
pamela.piovezan@ctmsp.mar.mil.br
thiago.carluccio@ctmsp.mar.mil

[2] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
alfredo@ctmsp.mar.mil.br
asantos@ipen.br

ABSTRACT

A new component named heavy reflector that did not exist in actual nuclear power plants was introduced recently by the EPR reactor. The component was designed to partially reflect neutrons inside the core to increase fuel efficiency and protect the vessel during its 60-year operational life.
Recently, an experiment was designed and performed to address the real neutron reflector contribution due to the stainless steel in the IPEN/MB-01 research reactor. The experiment consisted of several plates of stainless steel which were conveniently positioned at water reflector region of the reactor core. The main experimental results were the critical control bank positions and reactivity as a function of the number of stainless steel plates. The main outcome of the experimental results showed a quite clear effect on neutron absorption and neutron reflection due to the stainless steel plates.
The objective of this preliminary work is to address theoretically this experiment using the diffusion theory code CITATION, besides existing evaluation using Monte Carlo (MCNP and Tripoli) and transport (TORT) codes, in order to verify the performance of diffusion theory for the reflector region.

1. INTRODUCTION

The evaluation of the neutron flux distribution inside all regions in a reactor core still demands considerable computational resources and direct transport solutions for the entire core is not affordable for day-to-day exploitation. In order to obtain reliable data at the core level, a common procedure is to use various stages of calculations interconnected together.

A reactor core is made of several materials. The relative geometric arrangement of fissile, absorbent, and coolant materials usually follows regular patterns (referred to as lattices) inside the core. Such lattices are composed of sub elements called unit cells that are repeated throughout the core. The general approach to account for heterogeneous lattice effects is to perform a detailed calculation of the flux distribution in a given unit cell (usually assuming there is zero net current across the boundary of the cell by considering periodic or reflexive boundary conditions) and then calculate the effective group constants characterizing one such

cell [1]: after being condensed in few energy groups the various multigroup cross sections characterizing materials in the cell are spatially averaged over the cell using the flux distribution as a weighting function. This procedure results in cell-averaged or so-called self-shielded group constants that can then be used in the analysis of reactor assemblies or of entire cores [2].

For daily analysis the core calculations are usually done with few energy groups under the Diffusion approximation. The basic assumption of the Diffusion theory is that the angular neutron flux is weakly dependent on angle in such a way that it can be adequately represented by only a linearly anisotropic angular dependence (i.e., the P1 approximation) [1]. Although not always accurate, diffusion solvers are invaluable in obtaining inexpensive reactor core data since it takes few CPU time to perform full reactor core simulations.

The major key for the success of Diffusion codes lies in the few group constants libraries. However, even for very accurate few group data, there are some limitations that are intrinsic to Diffusion approximation. It is textbook knowledge, for example, that in the neighborhood of heavy absorbers the Diffusion approximation loses its strength [1, 2].

In practice, on the other hand, it is quite common to have materials in the reactor core and reflector that have high cross section for neutron absorption. As an example, a new component named heavy reflector was introduced recently by the EPR reactor. This SS component was designed to partially reflect neutrons inside the core to increase fuel efficiency and protect the vessel during its 60-year operational life [3]. Even with the presence of such materials in the reactor core, the diffusion theory is still used to describe the core.

In order to quantify the performance of diffusion theory for a high absorption material in the reflector region, the Heavy Steel Reflector experiment performed in the IPEN/MB-01 research reactor facility was selected as a reference. In this experiment, several plates of SS-304 (3 mm thick) were introduced as SS reflector in the west face of this reactor and several quantities such as critical control bank configuration and reactivities were measured as a function of the number of plates [4, 7].

In this work, we present the preliminary results of using the HAMMER code to generate 1-D few group diffusion constants for the heavy reflector experiment on the research reactor. These constants were used in the CITATION diffusion code to investigate the effects of a high absorption material on the neutron multiplication factor and reactivity estimates.

2. THE IPEN/MB-01 HEAVY REFLECTOR EXPERIMENT

The IPEN/MB-01 reactor core is located inside a cylindrical open-top moderator tank which has 1830-mm outside diameter, is 2750 mm high, 8.5 mm thick, and is made of SS-304. Demineralized light water is used as moderator. Several configurations of cylindrical fuel rods can be arranged in square uniform lattices of 15.0 mm pitch as three grid plates assure the rods' positions. All grids have a square shape (side length is 588 ± 0.5 mm) and are made of SS-304. The bottom grid plate is 22 mm thick and consists of a 30 x 30 square array out of which 852 are 10.4-mm-diameter cavities (not holes), whose purpose is to support the fuel rods. The remaining 48 positions are holes used to fix the guide tubes for the control and

safety rods. The intermediate and upper grid plates are located well above the active region and were not considered in this analysis.

Each fuel rod consists of a cladding (SS-304), low enriched (4.3486 wt.% 235U) UO2 pellets, alumina (Al2O3) pellets, a spring (Inconel-600), spacer tube (SS-304) and top and bottom plugs (SS-304). Their dimensions are shown in Figure 1. For this study, we considered fuel rods containing UO2 arranged in a 28x26 configuration, as shown in Figure 2.

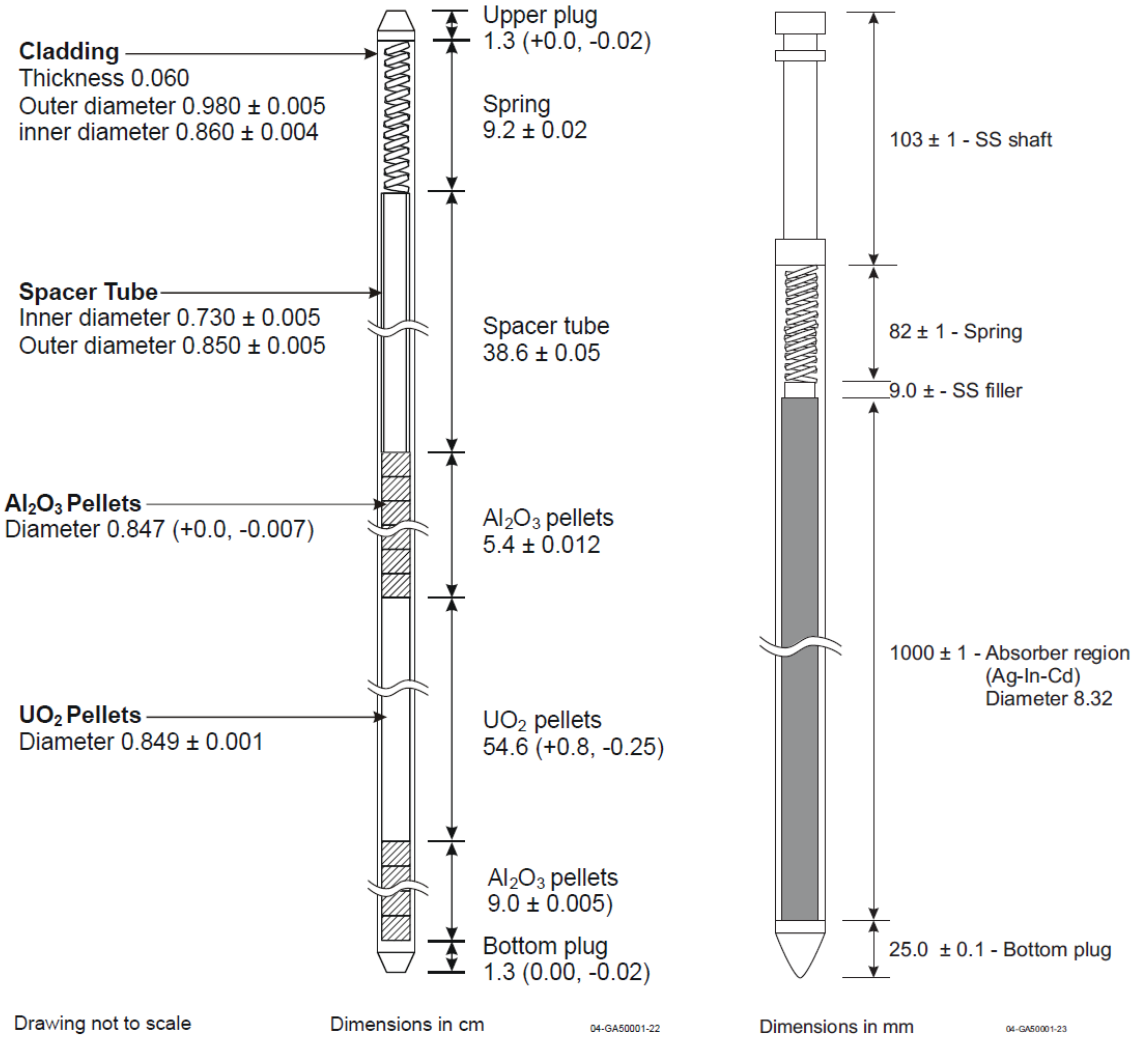

Figure 1. IPEN/MB-01 fuel and control rods dimensions.

Two banks of control rods control the IPEN/MB-01 reactor. They are located diagonally opposite each other in the core (the blue color in Figure 2 refers to the two control-bank locations, while the red color refers to the locations of the two safety-rod banks). Each of the four control and safety banks is composed of 12 rods held together and supported by a control mechanism above the tank. The absorber rods are clad by SS-304 and the end plugs are made of SS-304. The control rods are filled with an alloy of Ag-In-Cd while the safety rods are

filled with B4C powder. The dimensions of the control rods are shown in Figure 1. The control and safety banks move through the core inside guide tubes made of SS-304. Their outer diameters are 12.00 mm and the inner diameters are 11.30 mm. Additional information can be obtained in [4].

A mechanism was specially designed and mounted at the west face of the IPEN/MB-01 core to hold and fix the SS-304 plates in the reflector region (Figure 2). The chosen distance between last fuel rod row and the first plate was 5.5 ± 1.0 mm. During the execution of the experiment, the safety rods were kept in the total withdrawn position. The critical control bank positions for both BC1 and BC2 at the same withdrawn level and the reactivity were measured as a function of the number of SS-304 plates [4, 7].

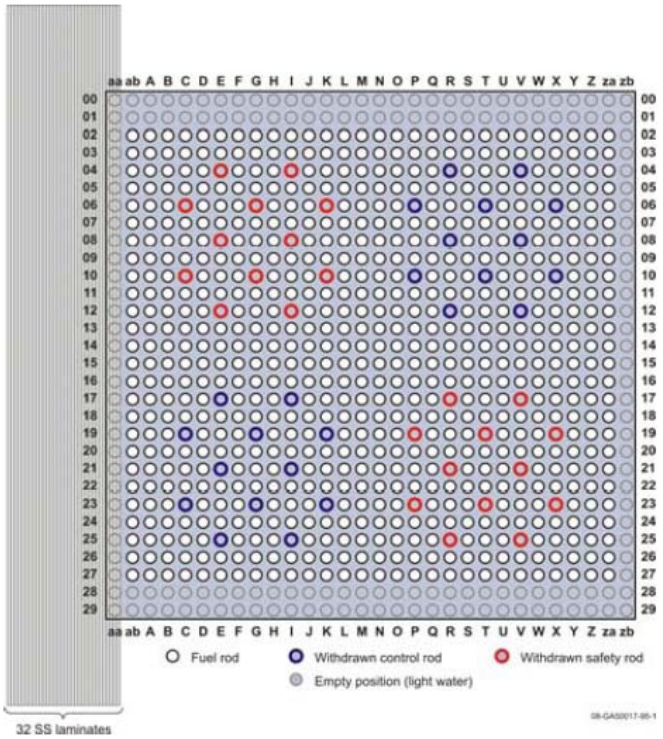

Figure 2. Experimental core configuration [7].

3. NUMERICAL CODES

This section describes the codes used in this analysis (CITATION and HAMMER) and the main assumptions adopted.

3.1 The CITATION code for reactor core model

The CITATION code was developed at Oak Ridge National Laboratory in 1971. It is a generic code that solves various kinds of up to 3D multigroup diffusion problems using a finite-difference method in space and time. The neutron-flux-eigenvalue problems are solved

by direct iteration to determine the multiplication factor or the nuclide densities required for a critical system [5]. This code was chosen because it is still used a lot in Brazilian organizations such as IPEN.

To model the IPEN/MB-01 reactor core in 3-D using the CITATION code some simplifications had to be made. In the z direction, eight plans were considered from top to bottom: the spacer tube plus control rod plan (25.0 cm high), the top alumina plus control rod plan (5.4 cm high), the active region plus control rod plan (z_2 = 54,6-2,5-z_1 cm), the active region plus control rod plug plan (2.5 cm high), the active region plus guide tube plan (z_1 cm), the bottom alumina plus guide tube plan (9.0 cm high), the bottom grid plate plan (2.2 cm high), and the bottom reflector plan (30.0 cm high).

In the xy direction, we considered a pin-to-pin model (1.5 cm pitch) surrounded by a 30.0 cm water reflector on each side. On the west side, there is additionally three regions between the last fuel rows and the 30.0 cm water reflector: a thin layer of water (0.55 cm thick), a variable layer of SS-304 (x = 0.3N cm thick, where N is the number of plates) and another water layer (y = 7.85–x cm thick).

For each one of these zones the macroscopic nuclear properties are assumed constant by the numerical code. The diffusion coefficient, the macroscopic absorption cross section, the macroscopic production cross section ($\nu\Sigma_F$), the macroscopic reciprocal velocity cross section and the macroscopic cross section for scatter from group K (above) to each of the other groups must be given as input data for CITATION.

The energy groups were divided in four ranges: from 1E-5 to 0.625 eV for group 4 (the thermal group), from 0,625 eV to and 5.53 keV for group 3, from 5.53 keV to 0.825 MeV for group 2, and from 0.825 MeV to 10 MeV for group 1 (the fast group).

3.2 The HAMMER-TECHNNION code for cross-section generation

The HAMMER-TECHNNION code (an acronym for Heterogeneous Analysis by Multigroup Methods of Exponentials and Reactors) was jointly developed at Brookhaven National Laboratory and at the Savannah River Laboratory in 1978 [6].

It performs a 1-D unit cell spectrum calculation using 54 fast and 30 thermal groups (obtained from ENDEF/B-IV microscopic cross section library), a detailed resonance treatment, a Fourier transform leakage treatment and integral transport theory for up to 20 spatial mesh points. Once the 54 and 30 neutron spectra are calculated, they are collapsed into four broad energy groups. Group constants are then obtained for the entire cell, each homogeneous region and combination of the homogeneous region.

To model the four-group constants for IPEN/MB-01 reactor core at HAMMER, ten unit cells were considered: three for the fuel rods (UO2, Alumina, and Spacer Tube), two for the control rods (Ag-In-Cd rod and its end fixture), one for the safety rods (guide tube only), one for the grid plate, one for the water below the grid plate, one for the water around the array and one for the heavy steel reflector.

Special attention was paid to the heavy reflector cell, since its cross sections were calculated several times for different SS-304 thickness. As illustrated in Figure 3, this cell was considered as four layers: a fuel plus water 5.0 cm layer for the neutrons spectrum, a thin layer of water (0.55 cm thick), a variable layer of SS-304 (x = 0.33N cm thick), and a 5.0 cm water layer.

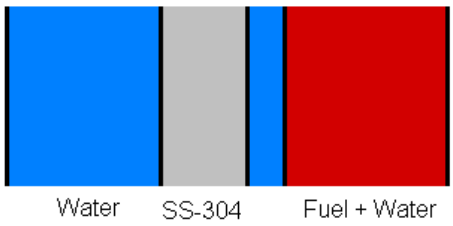

Figure 3. Cell model for the heavy steel reflector.

4. RESULTS AND DISCUSSION

Table 1 contains the main results for the k-effective and reactivities estimates for up to 15 SS-304 plates. The experimental reference values for reactivities inserted for the SS-304 plates are also in Table 1 for comparison.

Table 1. Diffusion estimates for k-effective and reactivity variation.

N	BC (%)	Experimental status	k_{eff}	$\Delta\rho_{calc}$ (pcm)	$\Delta\rho_{ref}$ (pcm)
0	58,12	Critical	1,007183	-212	-280
1	58,12	Subcritical	1,005036		
1	60,9	Critical	1,007430	-86	-94
2	60,9	Subcritical	1,006555		
2	61,87	Critical	1,007355	-32	-41
3	61,87	Subcritical	1,007034		
3	62,3	Critical	1,007382	-4	-13
4	62,3	Subcritical	1,007341		
4	62,43	Critical	1,007446	4	32
6	62,43	Supercritical	1,007489		
6	62,16	Critical	1,007271	23	29,6
7	62,16	Supercritical	1,007508		
7	61,86	Critical	1,007661	34	30,5
8	61,86	Supercritical	1,008004		
8	61,54	Critical	1,007258	14	21,5
9	61,54	Supercritical	1,007403		
9	61,32	Critical	1,007222	44	56,5
11	61,32	Supercritical	1,007673		

N	BC (%)	Experimental status	k_{eff}	$\Delta\rho_{calc}$ (pcm)	$\Delta\rho_{ref}$ (pcm)
11	60,74	Critical	1,007189	67	66,5
13	60,74	Supercritical	1,007866		
13	60,06	Critical	1,007290	49	49
15	60,06	Supercritical	1,007783		
15	59,55	Critical	1,007344	--	--

From Table 1, one could notice the k-effective for the experimental critical configurations are around 700 pcm supercritical for all simulated cases. The differences in reactivity due to the SS-304 plates, on the other hand, are relatively close to the experimental values. These results suggest that whatever is causing the overestimate in k-effective, it has been cancelled when the relative difference in k-effective is considered in order to estimate the reactivity inserted by the SS-304 plates.

However, it must be emphasized that these results seems to be very sensitive to the mesh size choices in HAMMER as well as in CITATION code for the region where the high absorptive material is considered. Additionally, as the control rods position change as more plates are inserted, the mesh size effects on axial direction might also play an important role. Consequently, a deeper sensitivity analysis must be conducted in order to investigate if the results presented above have a real physical meaning or if they are just the result of a “good” choice of meshes.

According to Dos Santos et al. (2008) [7], the heavy steel reflector behaviour by varying SS thickness is explained as the competition between the effect of thermal neutron capture by SS and the effect of fast neutrons back scattering to the core. The capture is preponderant for small thicknesses of SS (about 1 or 2 cm), whereas scattering effect increases with the SS thickness (in particular, the mean free path for fast neutron in SS in relationship with the inelastic scattering reaction is more than 10 cm). Then, it may also be interesting to consider a more complete scattering matrix estimate, as the HAMMER code are able to calculate only the removal cross section from group K to group K-1.

5. FINAL REMARKS

The results presented here are the first ones in order to quantify the performance of the diffusion code CITATION for the Heavy Steel Reflector experiment performed in the IPEN/MB-01 research reactor facility. Although there is a general overestimate in k-effective, the results comparisons with the experimental data for the reactivity induced by the SS-304 plates are relatively close. However, a much deeper analysis must be conducted in order to quantify the sensitivity of these results on mesh sizes on SS-304 regions for cross sections generation and for the diffusion calculation, as well as the effect of a better estimation of the scattering matrix in the diffusion estimates.

REFERENCES

1. J.J. Duderstadt and L.J. Hamilton, *Nuclear reactor analysis*, John Wiley and Sons, New York, USA (1976).
2. Y. Azmy and E. Sartori, *Nuclear Computational Science*, Springer Verlag, New York, USA (2010).
3. Golfier, H., et al. "Deterministic and Monte-Carlo calculation schemes of the EPR core and its heavy steel reflector." *ANS Topical Meeting on Reactor Physics PHYSOR-2006, Vancouver, BC, Canada*. 2006.
4. Dos Santos et al, "LEU-COMP-THERM-043 critical loading configurations of the IPEN/MB-01 Reactor with a Heavy SS-304 Reflector". 2008.
5. Fowler, T. B.; Vondy, D. R. e Cunninghan, G. W.; "Nuclear Reactor Core Analysis Code: CITATION", *ORNL-TN-2496 Rev.2*, ORNL, 1971.
6. J. Barhen et all; "The HAMMER Code System", *EPRI-NP-565*, 1978.
7. Dos Santos, et al. "Heavy reflector experiment in the IPEN/MB-01 reactor". *International Conference on the Physics of Reactors "Nuclear Power: A sustainable Resource", Interlaken, Switzerlan*. September 14-19, 2008.