Validation of Updated Neutronic Calculation Models Proposed for Atucha-II PHWR. Part II: Benchmark Comparisons of PUMA Core Parameters with MCNP5 & Improvements Due to a Simple Cell Heterogeneity Correction

C. Grant[2], R. Mollerach[1], F. Leszczynski[2], O. Serra[2], J. Marconi[2], and J. Fink[1].
[1]*Nucleoeléctrica Argentina S.A., Arribeños 3619, Buenos Aires (1429), Argentina*
[2]*Comisión Nacional de Energía Atómica, Av del Libertador 8250, Buenos Aires (1429), Argentina*

Abstract

In 2005 the Argentine Government took the decision to complete the construction of the Atucha-II nuclear power plant, which has been progressing slowly during the last ten years.

Atucha-II is a 745 MWe nuclear station moderated and cooled with heavy water, of German (Siemens) design located in Argentina. It has a pressure vessel design with 451 vertical coolant channels and the fuel assemblies (FA) are clusters of 37 natural UO_2 rods with an active length of 530 cm. For the reactor physics area, a revision and update of reactor physics calculation methods and models was recently carried out covering cell, supercell (control rod) and core calculations.

This paper presents benchmark comparisons of core parameters of a slightly idealized model of the Atucha-I core obtained with the PUMA reactor code with MCNP5. The Atucha-I core was selected because it is smaller, similar from a neutronic point of view, more symmetric than Atucha-II, and has some experimental data available.

To validate the new models benchmark comparisons of k-effective, channel power and axial power distributions obtained with PUMA and MCNP5 have been performed. In addition, a simple cell heterogeneity correction recently introduced in PUMA is presented, which improves significantly the agreement of calculated channel powers with MCNP5. To complete the validation, the calculation of some of the critical configurations of the Atucha-I reactor measured during the experiments performed at first criticality is also presented.

KEYWORDS: Atucha-I, Atucha-II, Reactor Physics Benchmarks, DRAGON, WIMS ,PUMA, MCNP5.

1. Introduction

In 2005 the Argentine Government took the decision to complete the construction of the Atucha-II nuclear power plant, which has been progressing slowly during the last ten years.

Atucha-II is a 745 MWe (2160 MWt) nuclear station, D_2O moderated and cooled, of German (Siemens) pressure-vessel design, located in Argentina. It has 451 vertical coolant channels and the fuel assemblies (FA) are clusters of 37 natural UO_2 rods with an active length of 530 cm. Power regulation is performed through absorber control rods made of hafnium and steel tubes which are located between rows of channels and enter the core slightly obliquely.

A revision and update of the reactor physics calculation methods and models was carried out covering cell, supercell (control rod) and reactor calculations. To validate the new methods and models, some benchmark comparisons with Monte Carlo calculations and with critical configurations measured during the first criticality experiments in Atucha-I were performed, and a selection of them are presented here. The core calculations were done with PUMA, a reactor code developed in Argentina, using cell cross sections obtained with WIMS-D5, and incremental cross sections of the reactivity devices obtained with DRAGON. More specifically, this report presents: a) A selection of benchmark comparisons of k-effective, channel powers, axial powers and reactivity worth of control rods between PUMA (3D diffusion code) and MCNP5 (Monte Carlo), b) Results of PUMA calculations of k-effective for some critical configurations measured in the first criticality experiments of Atucha-I. A separate report contains cell and supercell comparisons [1] and a description of the programs and models used to calculate lattice cell properties and control-rod incremental cross sections. In addition, a simple cell heterogeneity correction recently introduced in PUMA is presented, which improves significantly the agreement of calculated channel powers with MCNP5.

Figure 1 and Figure 2 show horizontal sections of the Atucha-II and the Atucha-I cores.

2. Description of the Cases Analyzed

2.1 Idealized Atucha-I Core Benchmark Problems Calculated with MCNP5

The benchmarks used for comparison with MCNP5 are based on the Atucha-I core because it has the same lattice pitch (27.2 cm), similar neutronic properties, a smaller size (253 channels), a more symmetric channel distribution than the Atucha-II core, and also because there are experimental results on critical configurations available. A set of representative problems were defined based on the conditions of the first criticality of Atucha-I with control rods withdrawn (12.7 ppm B in moderator and coolant at an isothermal reactor condition at 60ºC, coolant purity 99.775 mol %) with small modifications to reduce the processing time of MCNP5 and avoid the generation of new cross section libraries.

The main modifications introduced for the idealized Atucha-I cell were: a) Temperatures were changed to 20.45 °C, (to avoid generating MCNP cross section libraries for 60 °C) ,although D_2O densities for 60 ºC were maintained. b) Pure zirconium was used instead of zircaloy (Zry). c) A 37 element FA was used because, while Atucha-I has 36 fuel rods in the FA with a structural rod (a Zr hollow tube in the outer ring), it was not possible to model the central FA in 1/6 or 1/12 MCNP core models.

The following 3D benchmark problems have been selected for this paper.

a) - 3D Idealized Atucha-I core with rods withdrawn

b)- (a) with 6 steel rods half inserted

c) - (a) with 6 hafnium rods half inserted

The axis of the first rod, extends from the upper plane of the active fuel zone, at the midpoint between channels Q27 and P28, to the mid-plane of the reactor, at the midpoint between M25 and N24 (angle with the vertical axis about 15°). The other five rods are obtained by reflection in the planes that determine the first 60º sector and corresponding symmetric planes, as indicated in Figure 2.

2.2 Atucha-I Critical Configurations Used for Experimental Validation.

From the measurements of critical configurations measured at first criticality of Atucha-I at

60 °C, two cases were selected, one with all control rods withdrawn, and another with maximum insertion of control rods. Atucha-I has 29 control rods, 3 made of steel, 24 made of hafnium, and 2 additional ones, (called partial rods) which are made of Zry with a partial length made of steel which were included to control possible axial xenon oscillations.

More specifically the critical configurations simulated were:

Cold condition T= 60º C, 12.7 ppm B, D_2O purity 99.775 mol %, all rods out.

Cold condition T= 60º C, 2.2 ppm B, D_2O purity 99.775 mol %, bank B (all rods except partial length rods 13 and 29) inserted 500 cm.

The cases with rods have all rods, except the two partial-length, ones inserted a large fraction of their length (full insertion 575 cm). To avoid errors associated with the dilution of the absorbing material of the rods in the whole z mesh interval, which would tend to increase the absorption of the last section of the rod, cases were calculated with insertions at the beginning and the end of the z mesh interval where the end of the absorbing material of the rod is located, and then interpolation was performed between these two cases to obtain the k-effective for the measured insertion.

Figure 1: Core section of Atucha-II

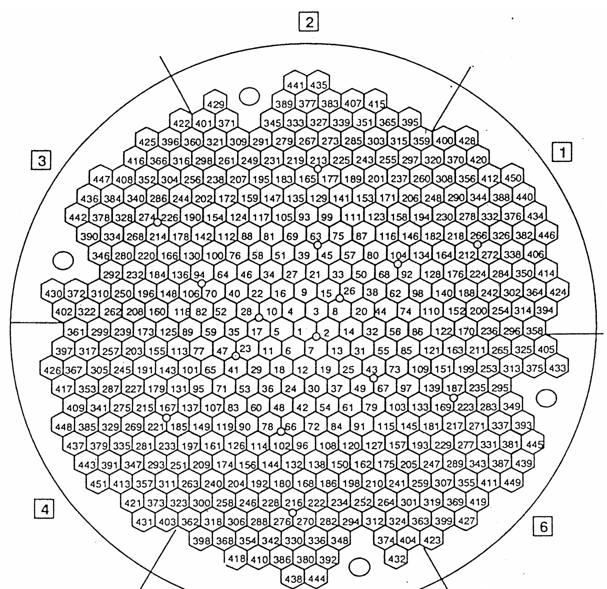
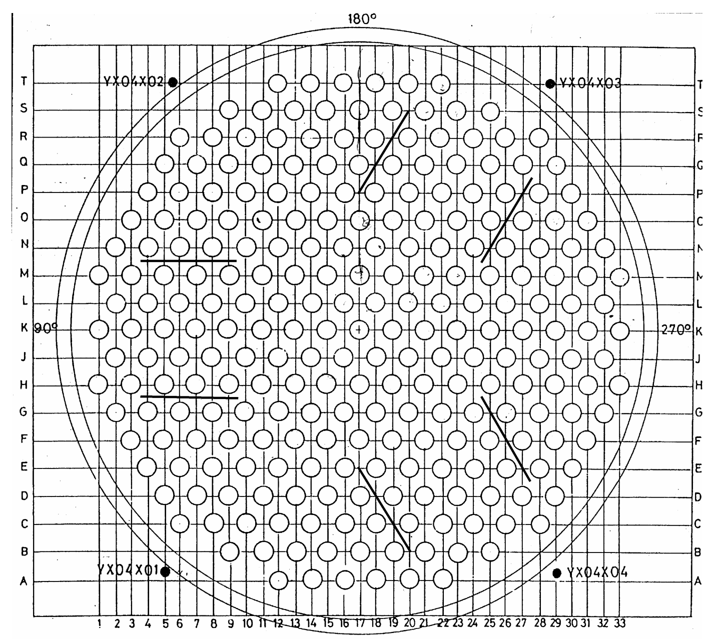


Figure 2: Core section of Atucha-I

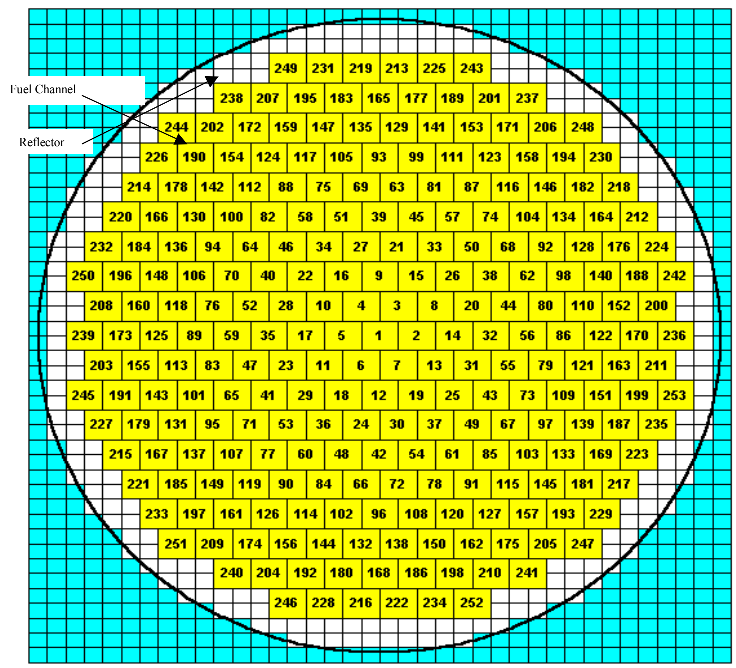


3. Description of Calculation Methods and Models

3.1 Brief Description of PUMA and its Models

PUMA is a 3D, mesh centered, finite difference, multigroup neutron diffusion program developed in Argentina [2], with additional capabilities for fuel management, space dependent xenon, and spatial kinetics. New and more detailed x-y-z models dividing the lattice cell in 4 or 16 rectangular mesh volumes (P4 and P16) were developed for Atucha-I and Atucha-II. The active region is divided into 20 equal axial sectors and each side of the axial reflector into 4 mesh intervals for both cases. The models represent the slightly oblique control rods as sections of rods parallel to the channels with the x and y coordinates coincident with the point of the mesh closest to the intersection of the rod axis with the mid-plane of the horizontal sector. The P16 model implies smaller deviations of the rod positions in the model with respect to the real ones. Two-energy-group cell and reflector cross sections were obtained with WIMS-D5 [3], and control-rod incremental cross sections with DRAGON [4]. Reflector cross sections were obtained as the two-energy-group cross sections of a thin outer ring of moderator at the cell boundary. Details of the cell and supercell methods and models can be seen in [1].

Figure 3: X-Y section of the Atucha-I PUMA model of 4 Mesh Volumes per Channel



3.1.1 Cell Heterogeneity Correction (CHC)

The diffusion equation used in PUMA can be written as:

$$\nabla \cdot (D_g \nabla \phi_g) - \Sigma_{Tg}\phi_g + \sum_{g' \neq g} \Sigma_{g'g}\phi_g + \frac{\chi_g}{k_e}\sum_{g'} \nu\Sigma_{fg'}\phi_{g'} = 0 \qquad (1)$$

This equation is solved using straight mesh-centered finite-difference discretization in x-y-z geometry. The neutron current continuity condition between a given mesh volume O and its neighbor at the right direction R, for each energy group g, is expressed as:

$$J_{S,g} = D_{R,g}\frac{\phi_{R,g} - \phi_{SH,g}}{\Delta x_R / 2} = D_{0,g}\frac{\phi_{SH,g} - \phi_{O,g}}{\Delta x_O / 2} \qquad (2)$$

where $\phi_{SH,g}$ represents the cell homogenized flux at the surface boundary S between O and R. For the other directions similar expressions can be written

This formalism assumes a homogenized cell and does not take into account the variation of ϕ_g inside the cell, because it establishes continuity conditions for the homogenized flux between neighbor elements. The cell heterogeneity correction includes this variation as follows:

Let us define the cell heterogeneity correction factors (CHC) $\beta_{O,g}$ (also called "discontinuity factors") as:

$$\beta_{O,g} = \frac{\phi_g(cell\ average)}{\phi_g(cell\ boundary)} \quad (3)$$

These are obtained from WIMS cell burnup calculations using the critical buckling, and depend on fuel type and fuel burnup. The fluxes in the cell boundary were obtained in a thin ring in contact with the cell boundary, which was also used to obtain reflector macroscopic cross sections. In homogeneous mesh volumes, such as the reflector, the $\beta_{O,g}$ are taken equal to 1.

$$\beta_{O,g} = \frac{\phi_{SH,g}}{\phi_{S,g}} \quad \text{(where } \phi_{S,g} \text{ is the flux at the cell surface for group g)} \quad (4)$$

These CHC factors are introduced in (2) to correct the surface fluxes.

$$J_{S,g} = D_{R,g}\frac{\phi_{R,g} - \beta_{R,g}\phi_{S,g}}{\Delta x_R/2} = D_{0,g}\frac{\beta_{O,g}\phi_{S,g} - \phi_{O,g}}{\Delta x_O/2} \quad (5)$$

The homogenized fluxes are replaced by their expressions as a function of the surface fluxes using the CHC factors, so the heterogeneous fluxes are correctly matched.

Finally,

$$J_{S,g} = \frac{1}{\frac{\Delta x_O}{D_{O,g}} + \frac{\beta_{0,g}\Delta x_R}{\beta_{R,g}D_{R,g}}}\phi_{O,g} - \frac{1}{\frac{\beta_{R,g}\Delta x_R}{\beta_{O,g}D_{O,g}} + \frac{\Delta x_R}{D_{R,g}}}\phi_{R,g} \quad (6)$$

As an example, for the Atucha-II full-power condition β_1 varies from 1.1718 for 0 burnup to 1.1681 for 8 MWd/kgU, and β_2 from 0.8958 to 0.8761. In the present implementation of CHC in PUMA, for cases with fuel burnup, β values averaged over the expected burnup range of the fuel with a uniform weight are used.

If the two neighbor mesh volumes have the same fuel type, then $\beta_{O,g} \sim \beta_{R,g}$ and equation (6) reduces to the homogeneous case. Therefore, the effect of this correction is mainly observed at the core channels in contact with the reflector or with different types of fuel.

3.2 Monte Carlo Calculations and Models

These were done with MCNP5 [5], using the endfb66 cross section libraries and the lwr60 and hwr60 thermal libraries. For the core calculations 1/6-core models were used. For the calculation of axial powers twenty axial intervals were used.

4. Results

4.1 Number of Cycles and Histories of the Core MCNP5 Calculations

The number of cycles and histories used in the MCNP5 calculations for the Atucha-I benchmarks is indicated in Table 1. The number of histories ranges between 146 and 193 Mh. Standard deviations for k-effective are between 6 and 7. 10^{-5}. For channel powers the standard deviations are between 0.04 % and 0.15% and for axial powers they are between 0.15% and 1.3 %.

Table 1: Atucha-I core 3D benchmarks. Number of histories of the MCNP5 Cases

	k-eff	σr (k-eff) (1.E-5)	σr(CP) min. (%)	σr(CP) max.(%)	σr(AP) min.(%)	σr(AP) max.(%)	hist.per cycle	cycles	Hist. (Mh)
3D-reference	1.00588	6.2	0.09	0.13	0.14	0.88	40000	4825	193.0
3D-6 oblique grey rods half inserted	1.00047	7.2	0.10	0.15	0.15	1.27	40000	3659	146.4
3D-6 oblique black rods half inserted	0.99827	6.8	0.10	0.15	0.14	1.42	40000	4059	162.4

CP: channel power. AP:axial power. σ_r: relative standard deviation of the MCNP results.

Table 2: 3D Atucha-I idealized core without control rods. Comparison of k_{eff} and channel and axial power distribution with MCNP5

	M5		P(16)	P(4)	P-CHC(16)	P4-CHC(4)
	x med.	3σr				
number of mesh volumes in a channel area			16	4	16	4
k-effective	1.00588	0.019%	1.00854	1.00854	1.00841	1.00844
Maximum Channel Power (MW)	9.127	0.27%	9.047	9.056	9.089	9.092
Location (channel)	K17		K17	K17	K17	K17
Rel. Discrepancy at MCP location			-0.87%	-0.77%	-0.41%	-0.38%
Maximum Axial Power (kW/53 cm)*	1273.3	0.85%	1261.6	1262.9	1267.5	1267.7
Location (channel-axial sector)	K17-6		K17-6	K17-6	K17-6	K17-6
Rel. Discrepancy at MAP location			-0.92%	-0.82%	-0.45%	-0.44%
Max. CP Rel. discr. with resp. to MCNP			3.37%	2.20%	0.59%	1.05%
Min. CP Rel. discr. with resp. to MCNP			-1.04%	-0.95%	-0.65%	-0.78%
RMS CP Rel. discr. with resp. to MCNP			1.23%	0.87%	0.37%	0.40%
Max. AP Rel. discr. with resp. to MCNP			5.30%	4.17%	2.43%	1.63%
Min. AP Rel. discr. with resp. to MCNP			-3.34%	-3.21%	-3.04%	-3.03%
RMS AP Rel. discr. with resp. to MCNP			1.61%	1.31%	0.95%	0.92%

4.2 Benchmark Comparisons of PUMA with MCNP5

Table 2 shows a summary of comparisons of k-effective and channel and axial power distributions for the 3D reference case without rods, for PUMA with 4 and 16 mesh volumes per channel (P4 and P16). To evaluate the influence of the statistical error in MCNP5 the maximum and minimum relative deviations in the MCNP5 cases for channel powers and axial powers should be considered. Considering an uncertainty of 3σr (an interval for more than 99% statistical confidence), it can be seen that the channel powers have uncertainties significantly smaller than the expected differences with PUMA, but some of the axial powers have uncertainties that are comparable to or larger than the differences with PUMA, so MCNP5 cases with a larger number of histories may be required for a consistent comparison of axial powers.

The maximum CP discrepancy with MCNP5 is 2.20% and 3.37 % for P4 and P16 respectively and the R.M.S. discrepancy is 0.87% and 1.23% respectively. The application of the CHC improves these values to 1.05%, 0.65%, 0.40% and 0.37% respectively.

Table 3 shows results for the case of 6 steel rods half inserted and for the case of 6 hafnium rods half inserted.

Table 3: 3D Atucha- I idealized core with six steel rods half inserted.
Comparison of k_{eff} and channel power and axial distribution with MCNP5

	MCNP5		P16	P4	P16-CHC	P4-CHC
	x avg	3σr				
k-eff (ref)	1.00588	0.019%	1.00854	1.00854	1.00841	1.00841
k-eff (case with rods inserted 50%)	1.00047	0.022%	1.00331	1.00343	1.00319	1.00333
Δk/k-eff(ref)*1000 (mk)	-5.38		-5.19	-5.07	-5.18	-5.05
Δk/k-eff/Δk/k-eff-1			-3.49%	-5.67%	-3.63%	-6.17%
MCNP 3σr unc. as % of Δk/k-eff (MCNP)		5.14%				
Maximum Channel Power (MW)	9.762	0.30%	9.627	9.640	9.687	9.678
Location	K17		K17	K17	K17	K17
Rel. Discrepancy at MCP location			-1.39%	-1.25%	-0.77%	-0.86%
Maximum Axial Power (MAP)(kW/53 cm)*	1388.7	0.85%	1365.8	1384.5	1397.0	1388.7
Location	K17-6		K17-6	K17-6	K17-6	K17-6
Rel. Discrepancy at MAP location			-1.65%	-0.30%	0.60%	0.00%
Max. CP Rel. Discrepancy with resp. to MCNP			3.13%	2.07%	0.32%	0.73%
Min. CP Rel. Discrepancy with resp. to MCNP			-1.44%	-1.25%	-0.85%	-1.27%
RMS CP Rel. Discrepancy with resp. to MCNP			1.18%	0.79%	0.43%	0.45%
Max. AP Rel. Discrepancy with resp. to MCNP			6.54%	4.83%	3.63%	5.00%
Min. AP Rel. Discrepancy with resp. to MCNP			-5.86%	-4.97%	-6.44%	-5.51%
RMS AP Rel. Discrepancy with resp. to MCNP			2.59%	1.74%	2.33%	1.59%

For the steel rods, the maximum CP discrepancy, in absolute value, for P4 and P16 is 2.07% and 3.13% and the R.M.S. discrepancy is 0.79% and 1.18% respectively. The application of the CHC improves these values to 1.27%, 0.85%, 0.45% and 0.43% respectively.

For the hafnium rods, the maximum CP discrepancy for P4 and P16 is 2.48% and 3.32%, and the R.M.S. discrepancy is 0.91% and 1.24% respectively. The application of the CHC improves these values to 1.65%, 0.89%, 0.46% and 0.32% respectively.

It must be noticed that the larger discrepancies without CHC occur at the channels at the core-reflector boundary in all cases and these show the largest improvement with CHC. For the internal FA, as expected, the improvement was much smaller, mainly due to a better balance of the entire power distribution.

4.3 Atucha-I Critical Configurations from the First Criticality Experiments

Table 5 presents calculated values of k-effective for two critical configurations measured during first criticality experiments in Atucha-I in 1974, using PUMA x-y-z models of 4 and 16 mesh volumes per channel, and with and without CHC. The table also includes an estimation of the influence on reactivity of the measurements errors, mainly on D_2O purity (0.005%) B concentration (0.2 ppm), temperature (2° C), and rod position (1 cm).

Table 4: 3D - Atucha- I idealized core with six hafnium rods half inserted. Comparison of k_{eff} and channel power distribution with MCNP5

	MCNP5		P16	P4	P16-CHC	P4-CHC
	x avg	3σr				
k-eff (ref)	1.00588	0.019%	1.00854	1.00854	1.00841	1.00841
k-eff. (case with rods inserted)	0.99826	0.020%	1.00097	1.00117	1.00085	1.00107
Δk/k-eff(ref)*1000 (mk)	-7.57	0.27	-7.51	-7.31	-7.51	-7.28
Δk/k-eff/Δk/k-eff(M5)-1			-0.77%	-3.45%	-0.89%	-3.81%
MCNP 3 sigma unc. as % of Δk/k-eff (M5)		3.63%				
Maximum Channel Power (MW)	9.971	0.27%	9.892	9.892	9.939	9.921
Location	K17		K17	K17	K17	K17
Rel. Discrepancy at MCP location			-0.79%	-0.79%	-0.32%	-0.50%
Maximum Axial Power (MAP)(kW/53 cm)*	1506.2	0.85%	1512.6	1499.8	1519.3	1505.2
Location	K17-6		K17-6	K17-6	K17-6	K17-6
Rel. Discrepancy at MAP location			0.42%	-0.43%	0.87%	-0.07%
Max. CP Rel. Discrepancy with resp. to MCNP			3.32%	2.48%	0.89%	1.65%
Min. CP Rel. Discrepancy with resp. to MCNP			-0.91%	-0.90%	-0.65%	-0.81%
RMS CP Rel. Discrepancy with resp. to MCNP			1.24%	0.91%	0.32%	0.46%
Max. AP Rel. Discrepancy with resp. to MCNP			5.64%	9.75%	4.24%	9.87%
Min. AP Rel. Discrepancy with resp. to MCNP			-8.28%	-7.33%	-9.47%	-8.42%
RMS AP Rel. Discrepancy with resp. to MCNP			3.15%	1.86%	3.02%	1.80%

The results are considered good, although the results show a slight underestimation of k-effective. For the reference case, k-effective values obtained are very close and between 0.99678 and 0.99686, with an experimental uncertainty of ±1.67 mk. For the case with 500-cm insertion of 27 rods, the k-effective values obtained by interpolation of values between 496 and 522.5 (which correspond to mesh boundaries in z) are between 0.99619 and 0.99772 with an experimental uncertainty of ±2.38 mk. The difference between the calculated k-effective of the two critical configurations range between 0.77 and –1.31 mk for the four PUMA cases, which can be considered within experimental error.

Table 5: K-effective values calculated with PUMA for some critical configurations measured during first criticality experiments performed in Atucha-I

Case	D2O B conc. (ppm)	Bank B position (cm)	P16	P4	P16-CHC	P4-CHC		Estimated k-effective measurement uncertainty (mk)
All rods out Prediction error (mk)	12.7	out	0.99696 -3.04	0.99696 -3.04	0.99678 -3.22	0.99681 -3.19	+/-	1.67
Bank B 496 cm inserted.	2.2	496	0.99734	0.99880	0.99665	0.99829		
Bank B 522.5 cm ins	2.2	522.5	0.98975	0.99168	0.98887	0.99113		
Bank B 500 cm (obtained by interp. of 3 and 4) Prediction error (mk)	2.2	500	0.99619 -3.81	0.99772 -2.28	0.99547 -4.53	0.99719 -2.81	+/-	2.38
Bank B 500 cm (obtained using 500 cm in PUMA)	2.2	500	0.99453	0.99614	0.99376	0.99554		
relative difference between calculated k-eff of critical condition with and without rods inserted in mk			-0.77	0.77	-1.31	0.38	+/-	4.05
reactivity effect of dilution of the incremental cross sections of the rod in the segment (496, 522.5) in mk			-1.66	-1.59	-1.71	-1.65		

5. Conclusions

As part of the activities associated with the revision and update of neutronic calculation methods and models for the Atucha-II nuclear power plant, benchmark comparisons of representative core calculations of channel powers and k-effective change with and without control rods for the Atucha- I power plant with PUMA and MCNP5 have been performed to validate x-y-z models recently developed of 4 and 16 mesh volumes per fuel channel and to evaluate the improvements associated to a cell heterogeneity correction recently introduced in PUMA. Three core problems based on an "idealized" Atucha-I cell, (one with all control rods withdrawn, one with 6 steel rods half inserted, and one with six hafnium rods half inserted) with lattice cell conditions similar to the ones at the first criticality of Atucha-I at 60°C, were used for comparisons with MCNP and two critical configurations (one with rods withdrawn and one with 27 rods inserted 500 cm) taken from first criticality measurements performed in Atucha-I in 1974 were also used as experimental validation.

The main conclusions are the following:

a) The predictions of PUMA using the new x, y, z models for Atucha-I, both for the benchmark comparisons with MCNP5 and for the critical configurations of Atucha-I, can be considered satisfactory.
b) The CHC improves significantly the agreement of channel powers with MCNP5, particularly for those channels located in the periphery of the core. The comparison of channel powers with MCNP5 in the three cases presented using the CHC shows RMS discrepancies of between 0.32 and 0.46 %, which are significantly better than without using the correction.
c) The comparisons of axial powers shows RMS agreements between 0.95% for the reference case to between 1.6 and 3.02 % for the cases with rods inserted. Considering the statistical uncertainties of the MCNP5 values of axial powers, it is probable that MCNP cases with a larger number of histories may be required for a more consistent comparison.
d) The calculation of two critical configurations measured during first criticality experiments in Atucha-I showed a very slight underprediction of k-effective, with values between 0.99619 and 0.99772, with an estimated effect on k-effective of measurement errors of D_2O purity, core temperature and B concentration and control rod position of ±1.67 mk and ±2.38 mk for the reference case and the case with rods inserted.

6. References

1) R. Mollerach et al. Validation of updated neutronic calculation models proposed for the Atucha-II PHWR. Part I: Benchmark comparisons of WIMS and DRAGON cell and control rod parameters with MCNP5 . Paper presented to this Conference.
2) C. Grant. PUMA version 4. Manual del usuario (PUMA version 4.User´s manual). Internal CNEA Report.
3) M. J. Halsall, et al. “WIMS-D. A neutronics code for standard lattice physics analysis”, distributed by the NEA Databank, NEA 1507/02 (1997).
4) G. Marleau et al. A user guide for DRAGON. Version DRAGON_000331 release 3.04. IGE-174 Rev.5. April 2000.
5) X-5 Montecarlo Team. MCNP- A general Monte Carlo N-particle transport code, Version 5. Volume II: User´s guide. LA-CP-03-0245 (2003).