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Development and Application of MCNP5 & KENO-VI Monte Carlo Models for the ATUCHA-2 PHWR Analysis

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ABSTRACT

The geometrical complexity and the peculiarities of Atucha-2 PHWR require the adoption of advanced Monte Carlo codes for performing realistic neutronic simulations. Core models of Atucha-2 PHWR were developed using both MCNP5 and KENO-VI codes. The developed models were applied for calculating reactor criticality states at beginning of life, reactor cell constants and control rods volumes. The last two applications were relevant for performing successive three dimensional neutron kinetic analyses since it was necessary to correctly evaluate the effect of each oblique control rod in each cell discretizing the reactor. These corrective factors were then applied to the cell cross sections calculated by the two dimensional deterministic lattice physics code HELIOS. These results were implemented in the RELAP-3D© model to perform safety analyses for the licensing process.

1 INTRODUCTION

In the framework of the agreement NA-SA – University of Pisa No. 2", several technical and research activities are being performed at the GRNSPG of the university of Pisa, in order to analyze the main characteristics of the plant and its behavior during normal and accidental conditions. In this paper we present the activities performed using the Monte Carlo MCNP5 and KENO-VI codes, or the Atucha-2 full core model development, some criticality calculations, its use for the RELAP5-3D© three-dimensional neutron kinetics model development and validation, then a result of a transient calculation using the validated RELAP5-3D© model.

Atucha-2 is a 693 MWe Siemens designed PHWR under construction in the Republic of Argentina. Its core is composed by 451 fuel bundles placed in vertical Fuel Channels which are arranged in a triangular lattice inside a large PWR-type Reactor Pressure Vessel (RPV). A 6 meter in diameter moderator tank is located inside the RPV, containing the moderator at the full operating pressure (11.5 MPa). Power control is achieved by changing the moderator temperature by an external cooling circuit, and by the use of 12 of the 18 oblique control rods.

Reactor shut-down is obtained by the all 18 oblique CRs and, during accidental conditions, by an emergency shut-down system injecting a highly concentrated boron solution in the moderator tank [4].

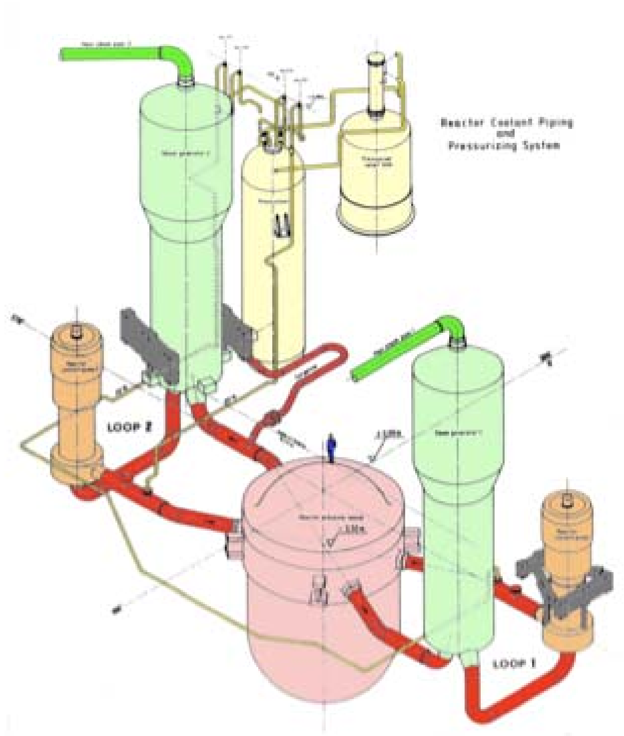

Figure. 1. Atucha-2 NPP Layout

After the definition of a relevant core status with fuel at the burnup equilibrium, a set of neutron cross section libraries were calculated by the lattice physics code HELIOS. These data were used for the setting up of a RELAP5-3D© Neutron Kinetic (NK) model of the core that was then coupled with a RELAP5-3D© Thermal-Hydraulic (TH) model of the whole plant. The TH model is based on a 280 Fuel Channels (FCs) and a 3D moderator tank nodalization. The 3D NK model is representing all the FCs, the reflectors and the oblique Control Rods (CR). The boundary conditions for the reconstruction of the boron clouds, injected in the moderator tank by the shut-down emergency system, were derived by previously executed Computational Fluid-dynamics (CFD) analyses by the CFX code [8].

The evolution of the boron concentration of the clouds was then reconstructed in the 3D TH moderator tank, using an automatic routine and several time-dependent junctions.

All these data were used as a Boundary and Initial Conditions (BIC) for the steady state and transients calculations.

2 MONTE CARLO MODELS DEVELOPMENT

The geometrical complexity of this design (e.g., oblique CR, each one divided in an upper and lower section, 451 independent FC, etc.), required the adoption of 3D Monte Carlo transport models (see Fig. 2).

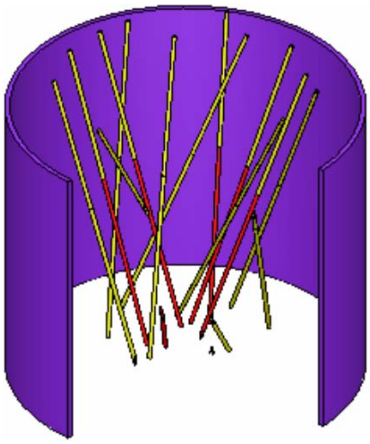

Figure. 2. Atucha-2 KENO-VI CR model.

Two independent, full core, pin-by-pin models were developed for the MCNP5 [1] and KENO-VI [2] codes, taking into account all the main characteristics e.g., the different insertion angles of the CRs and their different upper and lower structure, FC Zircaloy insulation sheets, the core barrel (see Fig. 3 and Fig.4).

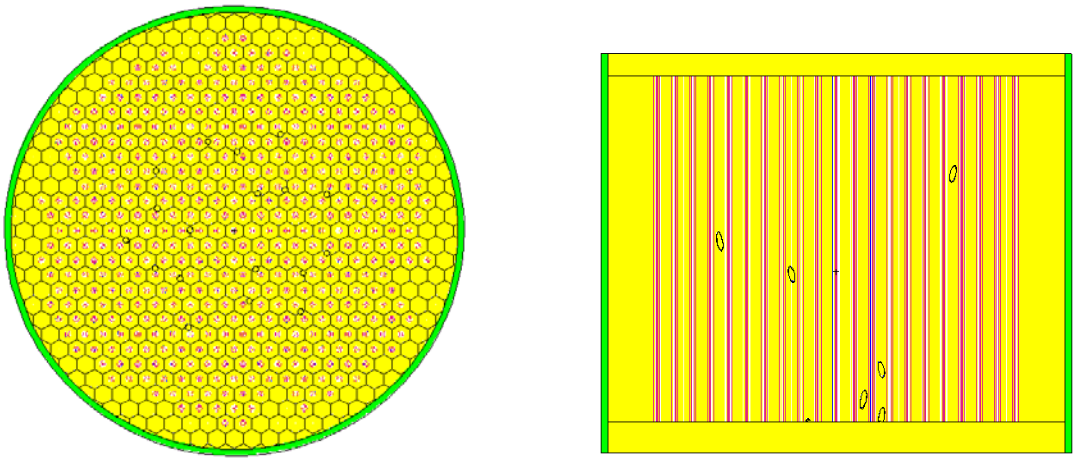

Figure. 3. Atucha-2 MCNP5 3D model, planar and axial view

These model were successfully used for CZP criticality calculation. Further development of these model consider 10 levels of axial discretization to take into account the axial differences in temperature and density.

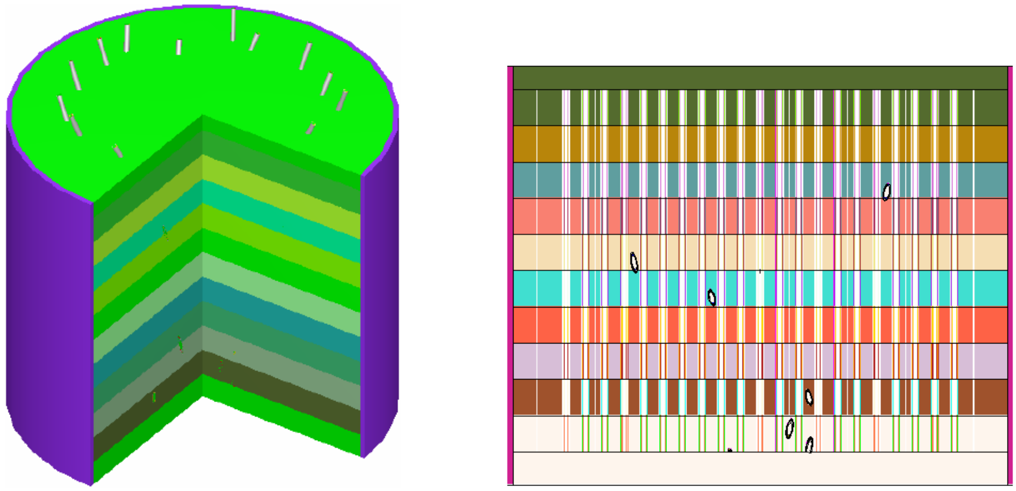

Figure. 4. Atucha-2 KENO-VI and MCNP5 models, ten level of axial detail.

3 SENSITIVITIES AND CRITICALITY CALCULATIONS

Preliminary criticality calculations were run at cold zero power (CZP) and sensitivities analyses were performed assessing the effects of several geometrical details on the results. The effects of initial source distribution and of different continuous energy (e.g., ENDF6.8, ENDF7) and multi-group cross sections libraries were also investigated. Results with low variance were obtained running about 100 million of active neutron histories. Finally reference criticality calculations were produced simulating CZP conditions for the core at the beginning of life (BOL).

Several cases were simulated to investigate the effects of control rod insertion, different Boron concentration, flux distribution and beta delayed factors. In Table 1 is reported the results of sensitivity of Boron concentration in the case of all rod inserted (ARI), then in Fig. 5 and Fig. 6 the flux distribution is given.

Table 1: Criticality results, CZP in ARI case from KENO-VI and MCNP5 core

Boron concentration [ppm]	**MCNP k_{eff}**	**σ [pcm]**	**KENO-VI k_{eff}**	**σ [pcm]**	**Differences (KENOVI - MCNP5) [pcm]**
0	1.08294	5	1.08753	6	459
16	0.96727	6	0.97153	6	426

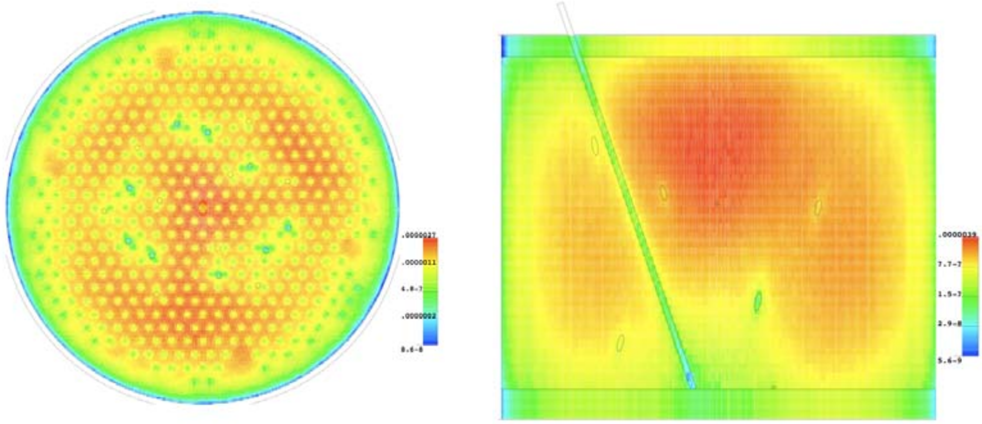

Fig. 5. Results from the Atucha-2 MCNP5 3D model – Thermal Flux distribution, planar and axial view.

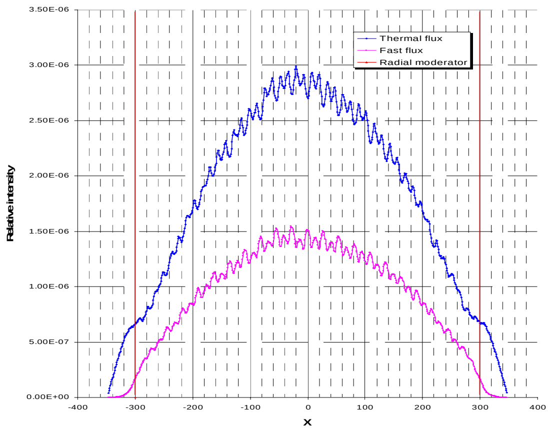

Fig. 6. Results from the Atucha-2 MCNP5 3D model – Thermal and Fast Flux distribution.

The agreement between both MCNP and KENO-VI codes was good with differences of the order of hundreds pcm. The MCNP5 CZP results were used in the validation process of the Atucha-2 RELAP5-3D© [3] 3D neutron kinetics (NK) – thermal-hydraulic model, also developed by the GRNSPG. Thus, a comparison between the CZP, all rods out solutions obtained by MCNP5 and the 3D NK NESTLE routine [5] of RELAP5-3D© was performed, allowing to validate both the applied coupling methodology as the system code model developed.

4 CR STOCHASTIC VOLUME CALCULATIONS BY MCNP5 MODEL

A further application of the developed Atucha-2 MCNP5 model was the stochastic volume calculations of the CRs [6].

As it can be easily understood from Fig. 7, each CR is intersecting in several different ways the various 4510 hexagonal prisms composing the 3D NK mesh structure of the NESTLE code. Therefore, in order to calculate appropriate CR weighting factors, several cases of intersection had to be identified and the relative cell CR volumes calculated.

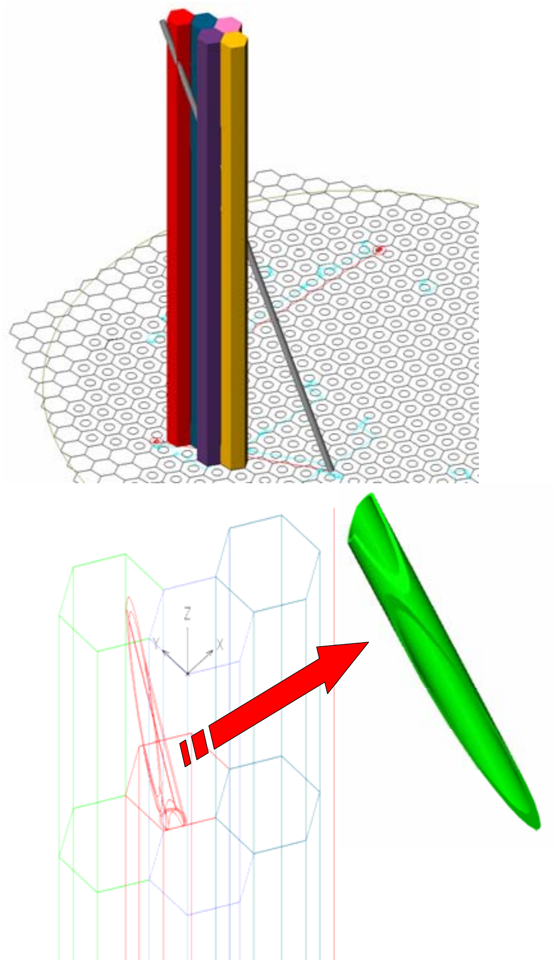

Fig. 7. Sketch of a CR and its crossing with 3D NK hexagonal cells.

The developed procedure was the following. The CR volume to be measured was enclosed in a sphere and an inward spherical distribution of neutron particles was employed for flooding the objects, i.e. the CR and the intersected hexagonal prisms. A flux tally got the resulting volume calculation (see Fig. 8).

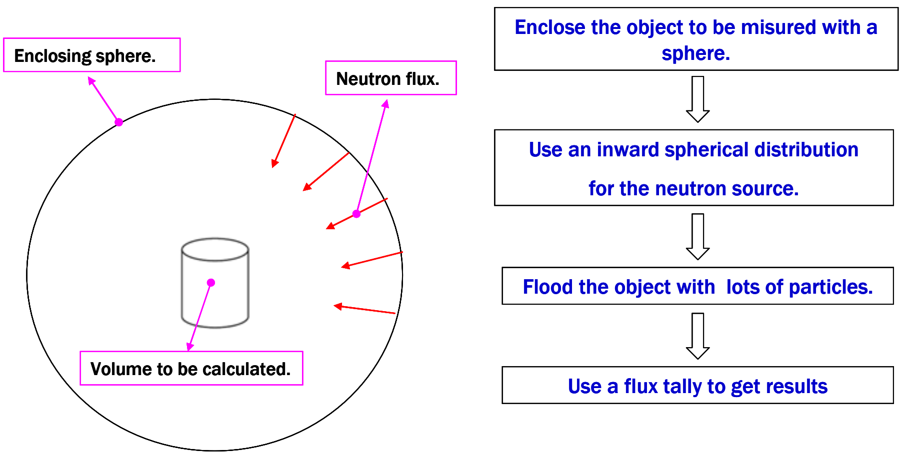

Fig. 8. Stochastic Cell Volume procedure by MCNP5 tally.

In order to get a low variance on each flux (i.e., volume) tally, an automatic C routine was developed for calculating the optimal dimension of the enclosing sphere. Moreover, 100 millions of neutron histories were employed to minimize statistical fluctuations.

This volume calculation procedure underwent to a validation process comparing volumes calculated by MCNP5 with volumes calculated by the Autodesk AUTOCAD^{TM} model, developed for a single CR (see Fig. 7). The error on the MCNP5 volumes calculations is about few percent, ranging from a maximum of +9.7% to a minimum of +0.34%. The average error on the whole calculations resulted to be about +2%.

A C/PERL routine allowed to automatically create the several MCNP5 input files for the calculations of the all possible CR volumes resulting from the intersection of the 18 CRs with 3D NK hexagonal meshes. Actually, symmetry considerations allowed to reduce the number of CRs intersections to be investigated to 10 CRs, thus resulting in 10*40 = 400 volumes calculations. In a successive step, the obtained values were integrated in an other procedure for the NESTLE CR Cross Section weighting.

5 CROSS SECTION EVALUATION

The MCNP5 core model was also applied for the calculations of corrective factors for the CR cross sections libraries. These libraries were developed using the two-dimensional lattice physics code HELIOS, that can not take into account the three dimensional geometrical effects (i.e., the oblique CR) [7], [8]. Therefore, MCNP5 calculations were run comparing results for the realistic model (right part, Fig. 9) with an HELIOS equivalent MCNP5 model (left part, Fig. 9).

Fig. 9. 2D HELIOS and 3D MCNP5 models.

The developed procedure allowed to evaluate the effects on a cell macroscopic cross sections (namely, the absorption and the fission cross sections) by the three dimensional geometry (see Fig. 10). For performing this estimation, the use of the MCNP5 tallies was exploited.

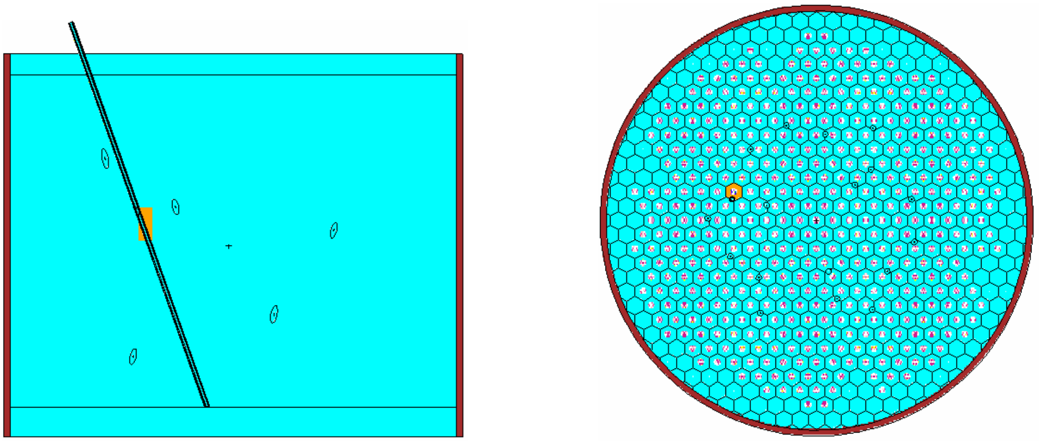

Fig. 10. Equivalent NESTLE composition in MCNP5 core model, axial view.

These averaged rate were obtained calculating with MCNP5 the reaction rate $R_{fiss,\ abs}$ in the selected “composition” (NESTLE equivalent 3D cell):

$$R_{fiss,abs} = (1/V)\int dEdV \sum{}_{fiss,abs}(E)\ \Phi(E) \qquad (1)$$

where $\Phi(E)$ is the flux, $\sum_{fiss,abs}(r,E)$ the macroscopic (fission or absorption) cross section and V the volume used to normalize the tally and calculated by MCNP5 with the stochastically method.

Thus, the averaged macroscopic cross sections $\overline{\sum_{a,f}}$ was easily obtained by the following formula,

$$\overline{\sum{}_{fiss,abs}} = \frac{R_{fiss,abs}}{\int \int dEdV\Phi(r,E)} \qquad (2)$$

Atucha-2 has two types of CR, differing by the absorber material (hafnium and stainless steel). For each type of CR, 5 cases were simulated, one considering an MCN5 model equivalent to the HELIOS model (straight CR) and 4 cases using a realistic MCNP5 model (oblique CR). Thus, the effects of possible insertion modes of the CR on the macroscopic cross sections were evaluated.

An example of results can be seen in Fig. 11, e.g. for gray (stainless steel) and black (hafnium) CRs. It is shown that, generally, a kind of linear law exists for the absorption cross section, with the increase of the ratio oblique volume/straight volume of a CR in the cell. The 3D effects seems neglible when considering the fast absorption cross section for the gray CRs.

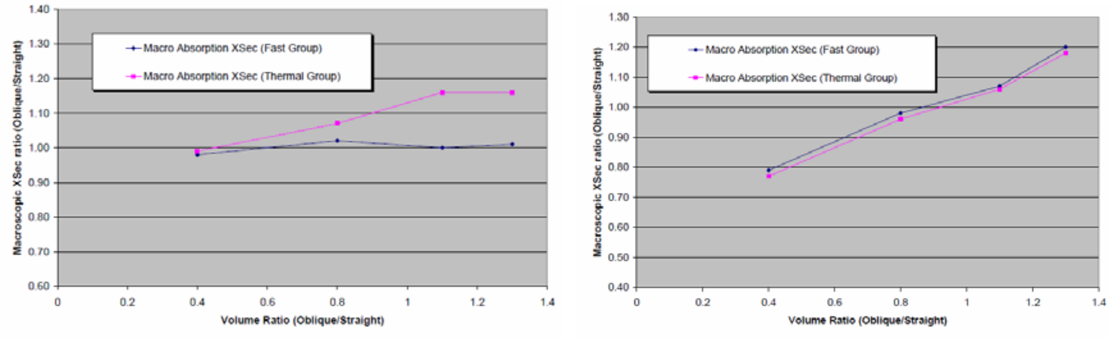

Fig. 11. 3D effects on Absorption Macroscopic Cross Sections (Gray CR and Black CR)

6 THE 0.1 LARGE BREAK LOCA

The results obtained by the Monte Carlo codes (i.e. the stochastically volume calculation and the corrective factor for the cross section) were implemented in the RELAP5-3D© Neutron Kinetic model. An application of this validated model is the 0.1 A Large Break LOCA in Cold Leg 2 (CL2), one of the Design Basis Accident (DBA) that has to be considered for the Atucha-2 licensing. The transient is initiated by the instantaneous opening

(i.e., 10-3 seconds) of the break located between the RPV nozzle and the CL2. Boron injection by the shut-down emergency system starts at +0.63 seconds from the beginning of the transient and terminates at +3.91 seconds. Scram signal is actuated after +0.07 seconds and the CR are completely inserted after +3.57 seconds. The transient analysis was performed for the first ten seconds. The results are presented in the Fig. 12 and Fig. 13.

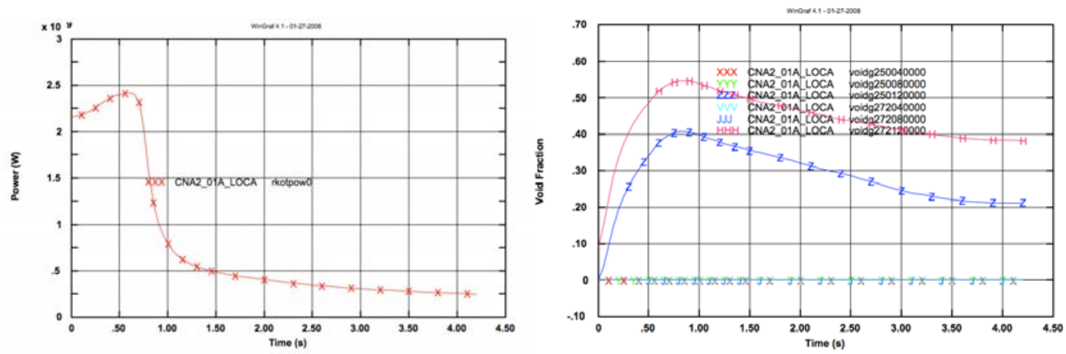

Fig. 12. Reactor Power (W) and void Fraction in central and hot channel

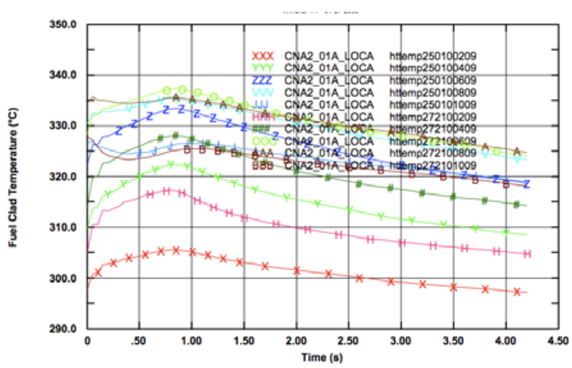

Fig. 13. Fuel Clad temperatures for Central and Hot Channel

As it is shown in Fig. 12 (left side) the power increases during the first half second of the transient because of the positive void coefficient. Fig. 12 (right side) represent also the void fraction trend for the central and hot channel. The actuation of the emergency boron injection system and CRs insert enough negative reactivity (see Fig. 12) to quench the power excursion. Fig.13 demonstrates that fuel clad temperatures are not of safety concern, also for the hot channel.

7 CONCLUSION

The complex Atucha-2 geometrical design required the adoption of advanced 3D Monte Carlo calculations. The capabilities of two of the most advanced codes (MCNP5 and KENO-VI) allowed to perform reference calculations with an unprecedented level of details. Moreover MCNP5 flexibility was exploited for an automatic calculation of CR weighting factors, allowing a great simplification of the necessary job for the 3D NK model development. Finally, further applications of these models are envisaged in the near future (e.g., criticality calculations with core at equilibrium burn-up).

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