A METHOD TO RESET A 3D ON LINE CORE MODEL ON INCORE MEASUREMENTS

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ABSTRACT

Core monitoring systems based on online 3D calculations need algorithms to permit to compensate the inaccuracies in the neutronic model and in the process and incore detectors signals. It is presented here a method to reset the core neutronic model in order the computed flux be in agreement with the detectors response. The method is based on an equivalence procedure which permits to determine a reset parameter, called pseudo buckling, acting on the data of the model. It will be then presented some results showing the performance of the method.

1. INTRODUCTION

Framatome ANP has recently developed a core monitoring system based on a 3D nodal model. This system, called US3D (3D Incore Surveillance Unit) [1], permits to evaluate the reactor safety margins during operation. The physical model is the same as the one used the reactor analysis system [2] employed in design calculations. It treats neutronics, thermohydraulics and nuclide depletion. The neutronic model implements the nodal expansion method. A deshomogenization procedure permits to evaluate pin by pin power distribution. This is called the theoretical power distribution. Another deshomogenization result is the theoretical response of the incore detectors.

Calculation results are combined with the incore instrumentation readings to obtain the so-called pseudo-experimental 3D pin by pin power distribution. Post processing modules take this power distribution as input in order to compute safety margins. When the difference between the theoretical and the pseudo-experimental power distributions becomes greater than a threshold, the model is reset. The reason of the discrepancies are the inaccuracies in the neutronic model and in the process and incore detectors signals. The reset procedure consists in evaluating some parameter to be introduced in the neutronic data in order to bring the theoretical power distribution closer to the pseudo-experimental one. At the center of the reset procedure there is an equivalence algorithm which is discussed in the next section.

Reset the model on the measurements has the immediate benefit of reducing the model uncertainty. As far as the results are closer to the measurements, the reset reduces also the risk of a drift of the model.

2. METHOD

The core model reset procedure is composed of two phases. The first phase is the determination of the so-called pseudo experimental neutron flux distribution by combination of the computed flux

distribution and the incore detectors signals. This is the target flux distribution to which the core model must be reset. The second phase is the reset parameter determination. The parameter that has been chosen is the pseudo transverse buckling. The reason of this choice is that the reset process can be seen as an equivalence procedure between the core model flux distribution and the pseudo experimental one. Framatome ANP employs a transverse buckling based procedure to perform equivalence between core models [3] and the method applied for this purpose has been extended to reset the core model on the measurements. The computation scheme is shown in Fig. 1. We will see in the next sections some details of the method used to determine the target (pseudo experimental) neutron flux distribution and a full description of the reset parameter determination method.

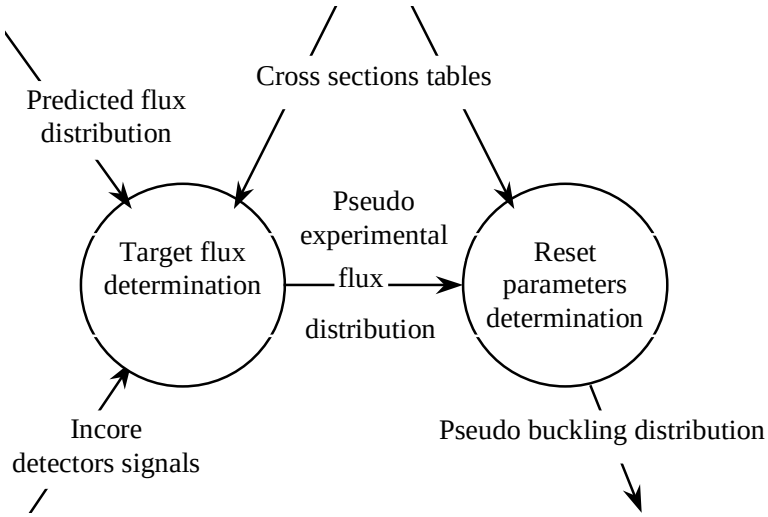

Figure 1. Reset procedure scheme

2.1 TARGET FLUX DISTRIBUTION DETERMINATION

The neutronic model reset algorithm takes as input the assembly homogenized pseudo-experimental power distribution. The computational procedure producing it is an extension of the one used to process the periodical incore flux maps. It consists in determining the difference between the measured and the predicted reaction rates in the detector positions and extending this difference on the whole core. The extension is performed by :

- construction of a reaction rate differences map via a polynomial fit,
- evaluation of the reaction rate difference at each potential detector location in each assembly axial node,
- conversion of the reaction rate difference into relative power density difference,
- application of this difference to the power distribution predicted by the neutronic model.

The result of the above procedure, constituted by several axial values of the power density for each assembly, is then extended to a value for each spatial node in each axial position. In our calculation there are 2 × 2 nodes per assembly per axial position. The extension is performed by using the intranodal power shape. The pseudo-experimental power distribution is then converted in pseudo-experimental fast and thermal neutron flux distribution. This conversion is done assuming that the local neutron spectrum is well predicted by the neutronic model. This assumption permits to set the following equation for each spatial node:

$$\frac{\Phi_{M,,n,1}}{\Phi_{M,n,2}} = \frac{\Phi_{C,,n,1}}{\Phi_{C,n,2}} \tag{1}$$

where $\Phi_{C,n,g}$ is the computed (or predicted) neutron flux and $\Phi_{M,n,g}$ is the measured (or pseudo-experimental) neutron flux in node n and energy group g.

Another equation is obtained writing the relation between the local power density, the energy production cross section and the neutron flux:

$$\kappa\Sigma_{f,,n,1}\Phi_{M,,n,1} + \kappa\Sigma_{f,,n,2}\Phi_{M,,n,2} = P_{M,,n,1} \tag{2}$$

The solution of the above equations set produces the pseudo-experimental neutron flux distribution, target of the reset parameter determination procedure.

2.2 RESET PARAMETERS DETERMINATION

The reset method equation is derived from the discretized form of the two groups diffusion equations.

$$\sum_{f=1}^{6}(\alpha_{n,n,1}\Phi_{C,n,1} - \alpha_{f,n,1}\Phi_{C,f,1}) + (\Sigma_{a,n,1} + \Sigma_{r,n})\Phi_{C,n,1} = \sum_{g=1}^{2}\frac{1}{k_{eff}}\nu\Sigma_{f,n,g}\Phi_{C,n,g} \tag{3}$$

$$\sum_{f=1}^{6}(\alpha_{n,n,2}\Phi_{C,n,2} - \alpha_{f,n,2}\Phi_{C,f,2}) + \Sigma_{a,n,2}\Phi_{C,n,2} = \Sigma_{r,n}\Phi_{C,n,1} \tag{4}$$

where index f indicates the faces of node n, $\Phi_{C,f,g}$ is the average predicted flux in the node beyond face f of node n, $\Sigma_{a,n,g}$, $\Sigma_{r,n}$, $\nu\Sigma_{f,n,g}$ are the average absorption, removal, neutron production cross sections in node n for group g and $\alpha_{f,n,g}$ are the coupling coefficients between the two neighboring nodes separated by face f.

Let us now introduce two transformations. First, let us introduce in the previous equations the pseudo-experimental flux distribution $\Phi_{M,n,g}$, in replacement of the predicted one $\Phi_{C,n,g}$. As these equations are not satisfied in consequence, we add some reset parameter in the loss term to compensate the error that has been introduced. The reset parameter B^2 is called pseudo-buckling because it has a role similar to that played by the transverse buckling in collapsing 3D models in 2D or in 1D.

Second, let us multiply and divide by $\Phi_{M,n,g}$ the leakage terms under the sum operators and introduce the following definition:

$$r_{f,n,g} = \frac{\Phi_{M,f,g}}{\Phi_{M,n,g}} \tag{5}$$

The term $r_{f,n,g}$ is the flux shape ratio in node n for group g and face f.

With these transformations, the modified discretized diffusion equation becomes, for the fast group:

$$\sum_{f=1}^{6}(\alpha_{n,n,1} - r_{f,n,1}\alpha_{f,n,1})\Phi_{M,n,1} + B_n{}^2 D_{n,1}\Phi_{M,n,1} + (\Sigma_{a,n,1} + \Sigma_{r,n})\Phi_{M,n,1} = \sum_{g=1}^{2}\frac{1}{k_{eff}}\nu\Sigma_{f,n,g}\Phi_{M,n,g} \tag{6}$$

and for the thermal group:

$$\sum_{f=1}^{6}(\alpha_{n,n,2} - r_{f,n,2}\alpha_{f,n,2})\Phi_{M,n,2} + B_n{}^2 D_{n,2}\Phi_{M,n,2} + \Sigma_{a,n,2}\Phi_{M,n,2} = \Sigma_{r,n}\Phi_{M,n,1} \tag{7}$$

The equations for B^2 are obtained by imposing the existence of the solution of the previous sets of equations. In fact, in writing the two groups neutron equation for node n on the form of Eqs. (6) and (7) we have transformed each of the n systems in homogeneous systems.

We can write them in matrix notation introducing the following 2×2 matrix:

$$H_n = L_n + B_n{}^2 D_n + A_n - \frac{1}{k_{eff}}F_n \tag{8}$$

where the matrix in the right side are defined as:

$$L_n = \begin{pmatrix} \sum_{f=1}^{N_f}(\alpha_{n,n,1} - r_{f,n,1}\alpha_{f,n,1}) & 0 \\ 0 & \sum_{f=1}^{N_f}(\alpha_{n,n,2} - r_{f,n,2}\alpha_{f,n,2}) \end{pmatrix} \tag{9}$$

$$D_n = \begin{pmatrix} D_{n,1} & 0 \\ 0 & D_{n,2} \end{pmatrix} \tag{10}$$

$$A_n = \begin{pmatrix} \Sigma_{a,n,1} + \Sigma_{r,n} & 0 \\ -\Sigma_{r,n} & \Sigma_{a,n,2} \end{pmatrix} \tag{11}$$

$$F_n = \begin{pmatrix} \nu\Sigma_{f,n,1} & \nu\Sigma_{f,n,2} \\ 0 & 0 \end{pmatrix} \tag{12}$$

The system composed by Eqs. (6) and (7) then becomes:

$$H_n \Phi_n = 0 \tag{13}$$

where Φ_n is a vector whose components are the fast and thermal fluxes.

This system admits a solution, i.e. a spectral flux shape in the mesh *n*, if the determinant of matrix H_n is zero. This is the condition permitting to evaluate the pseudo buckling in each node. The equation for B_n^2 is then:

$$\det(H_n) = 0 \tag{14}$$

which becomes:

$$\begin{aligned}&(\sum_{f=1}^{N_f}(\alpha_{n,n,1} - r_{f,n,1}\alpha_{f,n,1}) + B_n{}^2 D_{n,1} + \Sigma_{a,n,1} + \Sigma_{r,n} - \frac{1}{k_{eff}}\nu\Sigma_{f,n,1})\\ &\times(\sum_{f=1}^{N_f}(\alpha_{n,n,2} - r_{f,n,2}\alpha_{f,n,2}) + B_n{}^2 D_{n,2} + \Sigma_{a,n,2}) - \Sigma_{r,n}\frac{1}{k_{eff}}\nu\Sigma_{f,n,1} = 0\end{aligned} \tag{15}$$

This is a second order equation and admits 2 solutions. Only one of them has a physical meaning. The other one leads to a negative group flux ratio. The term B_n^2 can be seen as the higher eigenvalue of the following matrix:

$$D_n^{-1}\left(\frac{1}{k_{eff}}F_n - L_n - A_n\right)$$

The flux solution of Eq. (13) corresponds to the spectrum in node *n*. But in the application of this method the flux is not computed because the information we need is B_n^2 only.

Introducing the B^2 spatial distribution in the neutronic model permits to bring the predicted power distribution closer to the pseudo-experimental one.

2.3 ALGORITHM IMPLEMENTATION

We have seen that the reset parameters are determined in order to force the computed flux distribution to be close as much as possible to the pseudo experimental one. Since the pseudo experimental flux is determined only in the fuel region (the only region where the detectors are located) we have no target in the reflector region. Hence the B^2 is set to zero in this region.

The equations shown in the previous sections take into account only the neutronic aspect. Modifying the power shape consequently to the application of the reset parameters has a feed back on the cross sections. For this reason the scheme shown in Fig. 1 is nested in a loop in which a thermohydraulic and fuel thermal calculation is performed. This ensures the coherence between the reset neutron flux distribution and the cross sections.

3. RESULTS

The reset method has been tested on a series of reactor configurations. Simulated configurations,

representative of normal plant operations and real configurations, based on incore measurements, have been studied. In the simulated configurations, pseudo-experimental results have been represented by a reference calculation. Deviation from the pseudo-experimental results has been represented by calculations performed introducing perturbations with regard to the reference configuration. The perturbation permits to simulate a discrepancy between the prediction and the measurements. A perturbation has been introduced also in the real configurations, in order to test the capability of the reset method to correct a drift. The reference results (pseudo-experimental flux distribution coming from simulation or measurements) and the perturbed model have been used as input to the module implementing the reset algorithm. The computed pseudo-buckling distribution has then been inserted in the theoretical model in order to obtain the reset model. The simulated configurations have been followed by a power operation transient in order to test the capability of the reset method to maintain the model close to the reference all along an evolution. For the real configurations, only an instantaneous evaluation has been made. We will see in the following sections two examples of this kind of calculations.

3.1 RESET ON A SIMULATED CONFIGURATION

This calculation has been performed on a 1300 MW core at the beginning of an equilibrium cycle. The reference starting configuration is a best estimate calculation in xenon equilibrium condition. A perturbation was introduced in order to simulate a drift of the model. It consisted in modifying the fuel exposure distribution up to 30 % in order to introduce an axial and radial perturbation on the neutron flux distribution.

This reset operation has been performed at the beginning of a load follow transient. This transient has been executed three times:

- with the reference model, to simulate a pseudo-experimental transient,
- with a perturbation, to simulate the theoretical model behavior,
- with a perturbation and the pseudo-buckling distribution, to simulate the reset model behavior.

The transient consisted in a reduction of the rated power by 50 % at a rate of 5 %/min and a return to full power after 5 hours. Grey control groups have been inserted during the reduced power operation.

A comparison on the power axial offset *AO* and power peaking factor *FQ* is shown in Fig. 2 and 3. These figures compare the time behavior of the reset model (*Reset* curve) to those of the perturbed model (*Pert.* curve) and reference model (*Ref.* curve). It can be seen that the use of the pseudo-buckling distribution compensates the effect of the perturbation all along the transient.

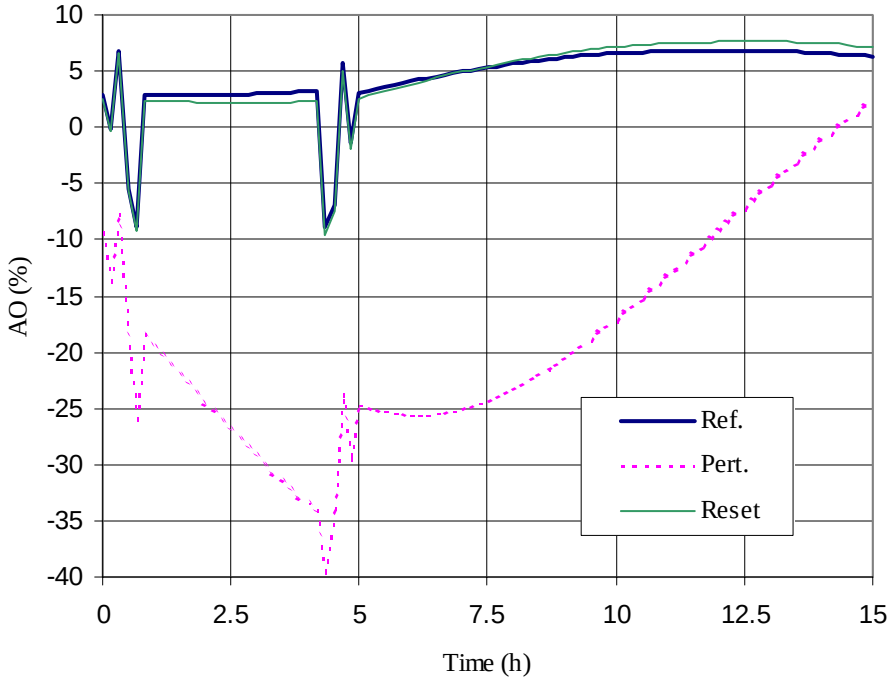

Figure 2. Time evolution of the power axial offset.

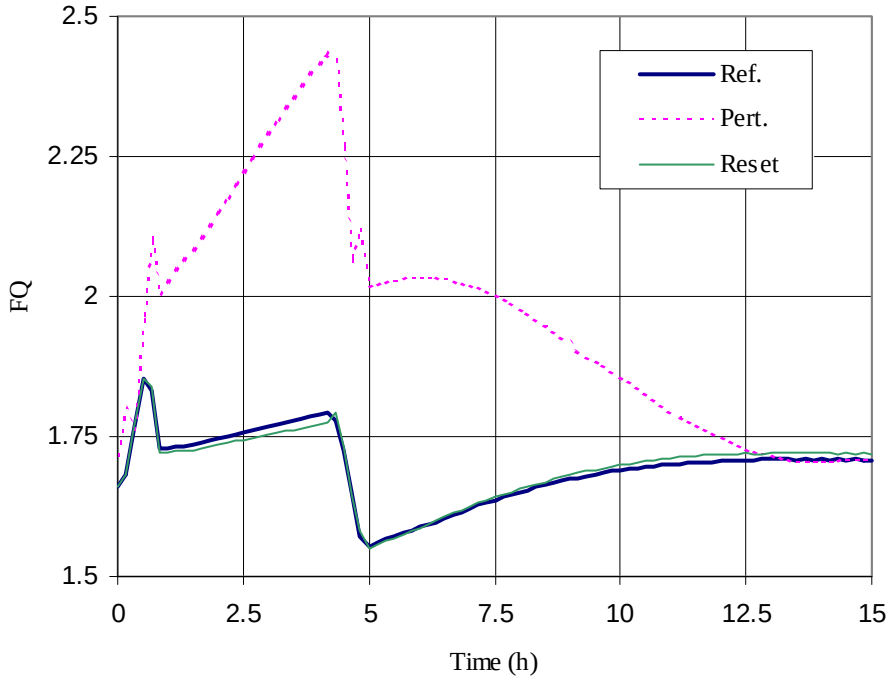

Figure 3. Time evolution of the power peaking factor.

3.2 RESET ON A REAL CONFIGURATION

This calculation has been performed on a 1300 MW core at 1000 MWD/T from the beginning of cycle 4 in xenon equilibrium condition. The reference starting configuration is a measurement reconstructed pseudo-experimental flux distribution obtained using the solution of Eqs. (1) and (2). The measurements correspond to a periodical flux map with travelling incore detectors. Since the US3D takes the information from fixed detectors, the rhodium collectrons, the flux map has previously reduced to represent the response of the collectrons. A perturbation was introduced in the model in order to simulate a drift. Without it the differences between the reference and theoretical calculation would be too small and the reset would be not useful. This perturbation consisted in modifying the fuel exposure distribution up to 30 %.

A comparison on the node wise local power, assembly wise power axial offset *AO* and assembly wise power peaking factor *FQ* is shown in Fig. 4, 5 and 6. The histograms appearing in these figures compare the error of the reset model (*Reset* histogram) to the one of the perturbed model (*Pert.* histogram). The error is the difference between the result of the reset or perturbed model and the reference model. It can be seen that the use of the pseudo-buckling distribution reduces drastically the error and its dispersion.

This kind of calculation shows the performance of the reset model when the reference flux distribution does not come from a diffusion calculation.

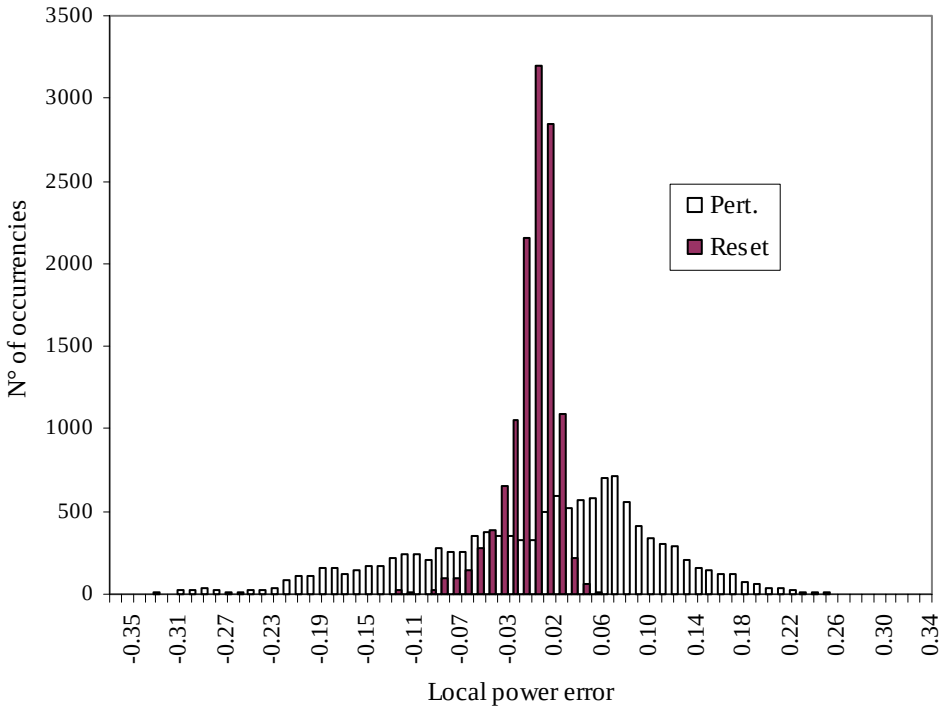

Figure 4. Error on the node wise local power with respect to the pseudo-experimental value.

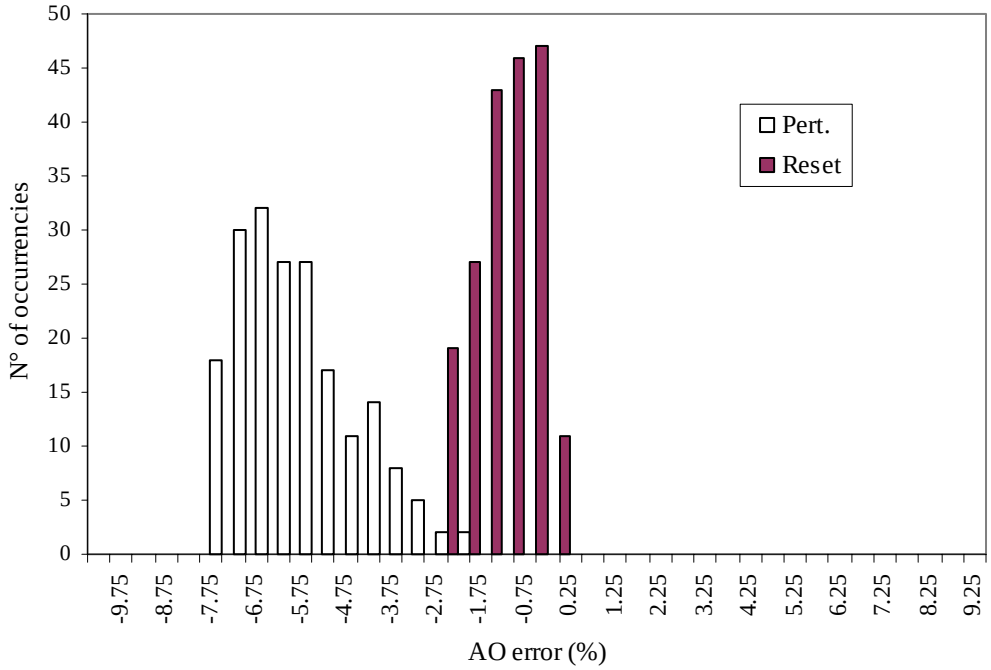

Figure 5. Error on the assembly power axial offset with respect to the pseudo-experimental value.

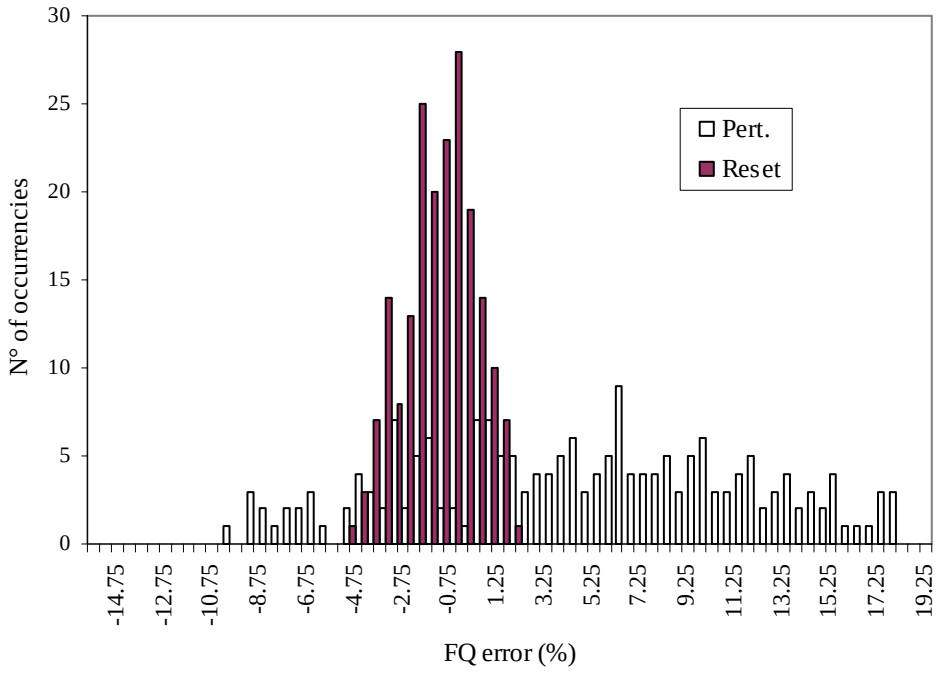

Figure 6. Error on the assembly power peaking factor with respect to the pseudo-experimental value.

4. PERFORMANCE REMARKS

If we compare the results shown in section 3.1 with the ones shown in section 3.2, we can see that the difference between the reset and reference model obtained in the case of real configurations is greater than the one obtained in the case of simulated configuration. This is due to the fact that in the case of simulated configurations the reference flux is known in all the regions of the model, and this feature stabilizes the algorithm. In the case of real configurations the reference flux is not known in the reflector and in this region no reset is done.

Another aspect that produces higher errors in the real configurations, is that in this case the reference flux does not satisfy rigorously the diffusion equation and the equivalence algorithm can not insure the reset flux to match exactly the reference. The reason can be understood if we write the reference flux (pseudo experimental) in the following form:

$$\Phi_{M,n,g} = \Phi_{C,n,g} + \delta\Phi_{n,g}$$

In the case of simulated configuration, the difference $\delta\Phi_{n,g}$ satisfies the diffusion equation. In the case of real configurations this is not true. This means that in solving the diffusion equation with the reset parameters the result fluxes will not satisfy exactly Eq. (5), because the fluxes appearing in Eq. (5) does not satisfy the diffusion equation. A discrepancy between the reset and the reference model will then exist. But this discrepancy is small and the benefit of the reset is maintained.

CONCLUSIONS

The method to reset a core model presented here is an extension of an equivalence method [3] used by Framatome ANP to collapse a 3D model into 2D or 1D. This method has always shown good results and for this reason has been chosen for the US3D. The examples shown in section 3, and the other tests performed to validate the method, demonstrate the capability of the pseudo-buckling to be a good reset parameter.

ACKNOWLEDGEMENTS

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