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Modeling Local History Effects in the Nodal Code ARTEMIS™

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Abstract - *The insertion of devices like control rods and detectors during reactor operation induces a non-standard depletion of the surrounding fuel pins. During the insertion period the pins experience a reduced pin power density and, therefore, a reduced fuel burnup and an off-nominal actinide and fission product buildup. The major consequence of this special depletion is that when the device is withdrawn the power peak could be higher than the result of the standard dehomogenization model. Modeling this phenomenon demands to take into account the history of the presence of the device. This paper describes the methodology implemented in ARTEMIS™ to evaluate the effect of these devices on the pin-wise power distribution.*

I. INTRODUCTION

The pin power distribution provided by ARTEMIS™ [1] is determined with a dehomogenization method based on single assembly calculations performed with APOLLO2-A [2]. The single assembly calculations include a depletion at nominal conditions and recovery cases at a variety of **state** conditions. Devices like detectors or control rods are assumed as withdrawn during the depletion. However, in reality, such devices can spend a long period inside an assembly and then be withdrawn from it. In this kind of situation, a classical dehomogenization procedure could not predict correctly the power distribution. In fact, during the insertion period the pins experience a reduced fuel exposure and a spectrum perturbation which is the cause of an off-nominal actinide and fission product buildup. The consequence of this special depletion is that at withdrawal, higher local pin powers occur in fuel rods adjacent to the guide tubes in which the device was inserted. Furthermore, the underestimated power could occur in the fuel rod with the maximum power. This phenomenon is illustrated in Fig. 1, which shows the pin power factor during a depletion where the control rod has been alternatively inserted and withdrawn. It can be seen that each time the control rod is withdrawn, after a period of insertion, the actual value of the pin power factor in the peak position is higher than the value estimated from the standard single assembly depletion. Neglecting to model this phenomenon could introduce inaccuracies and drive to non-conservative results; therefore a local history model (LHM) that accounts for this effect on pin power is necessary.

To overcome the weakness of the traditional methodology, which neglects this kind of effects, several approaches have been developed inside nodal codes. One of these implements an assembly submesh actinide tracking model, which enables to represent exposure-induced pin power variations [3]. Another method to better predicting pin power for the core operated with control rod insertion has been developed via a pseudo pin-by-pin calculation methodology [4,5]. This paper describes the methodology implemented in the AREVA NP's nodal code ARTEMIS™.

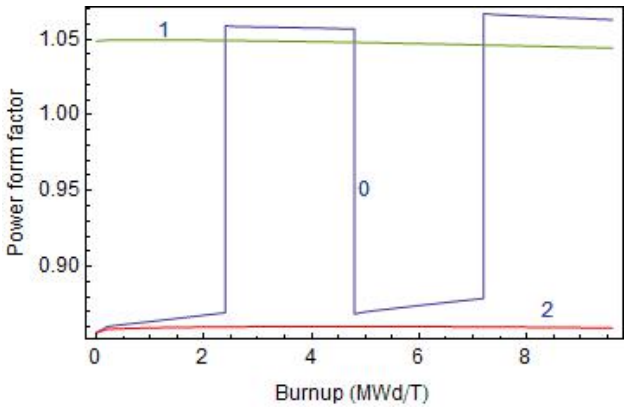

Fig. 1. Pin power factor during single assembly depletion in different conditions. 0: the control rod has been alternatively inserted and withdrawn. 1: the control rod is permanently withdrawn. 2: the control rod is instantaneously inserted.

II. METHOD

In the following section the general description of the method is done and followed by the description of the procedure that implements the method.

1. General Description

Let us imagine that we could perform with the lattice transport code APOLLO2-A the depletion of each assembly in the real physical conditions observed by each assembly in the core, with the standard single assembly reflective boundary conditions (B.C.). Performing a dehomogenization using as input the pin power distribution provided by these calculations would provide a more realistic pin power distribution, one that accounts for local history effects. The idea of the method is to execute in an approximate way the

single assembly depletion with the device inserted (or withdrawn after a continuous insertion) inside the core code ARTEMIS^{TM}. However the problem of the computation time and accuracy rises:

- Performing a transport calculation with the accuracy of APOLLO2-A would be an unacceptable computational burden;
- Using a too simplistic solver would deteriorate the quality of the results.

The solution that has been adopted is to perform two calculations with an approximate formulation of the transport: the two-group collision probability (Pij), which is very cheap in computation time. The algorithm has been implemented as described in [6]. The first calculation is performed with the real conditions (but with reflective B.C.), the second one with the conditions used by APOLLO2-A to generate the dehomogenization data. The difference between the flux solutions of these calculations is added to the pin-by-pin flux distributions, which are interpolated from the libraries as usual. Doing that, the assumption is made that this difference is very close to the one that would have been computed between two APOLLO2-A calculations in the same conditions. A verification of this assumption has been done during a preliminary study. The approximation has been found satisfactory.

To perform the approximate calculations described above, pin-by-pin cross section distributions are necessary. For this purpose pin-cell-type cross sections and Pij data are taken from APOLLO2-A with the pin burnup as sole independent parameter for each fixed assembly-wise state. An equivalence procedure, based on the SPH factors, is applied in order to make the Pij calculation consistent with the APOLLO2-A calculation. Thanks to this equivalence, a calculation performed by ARTEMIS^{TM} on a configuration having the same local parameters of the APOLLO2-A calculation, gives the same result. Each pin has its own data set.

A linear interpolation is performed for the cross sections and Pij probabilities as a function of the pin burnup. The cross sections are assumed to depend on the pin burnup and on a parameter p_{hist} taking into account spectral effects. This interpolation method differs from the one that is applied for the nodal cross sections in ARTEMIS^{TM}, which is based on 4 sets of B-splines, each one function of 3 parameters between: burnup, ^{10}B nuclide density, ^{135}Xe nuclide density, H_2O molecular density, fuel temperature, and moderator temperature. Within the LHM, the determination of reaction *x* cross section is performed for each energy group with the following expression:

$$\Sigma_{x,pert}(Bu, p_{hist}) = \Sigma_{x,ref}(Bu + \Delta Bu)(1 + C_1 \Delta p_{hist} + C_2 \Delta p_{hist}^2) \quad (1)$$

where we have made the following definitions:

- p_{hist} parameter representing the cumulated history effect of the spectrum on the pin composition,
- $\Sigma_{x,ref}$ cross section of reaction *x* interpolated versus burnup,
- ΔBu difference in burnup between the real depletion and the depletion assumed by APOLLO2-A to compute the pin flux distribution used by the dehomogenization module (cf. sec. II.2),
- Δp_{hist} difference in cumulated effect of the spectrum between the real depletion and the depletion assumed by APOLLO2-A (cf. sec. II.2),
- C_i (i=1,2) coefficients associated to a fuel type, to be defined with APOLLO2-A calculation with the device inserted.

The parameter p_{hist} used to account for spectral history effects is the ratio between the nuclide densities of ^{239}Pu and ^{238}U:

$$p_{hist} = r_{Pu/U} = \frac{N_{Pu239}}{N_{U238}}. \quad (2)$$

The expression giving the time integration of $r_{Pu/U}$ is:

$$r_{Pu/U}(t + \Delta t) = \frac{(\sigma_{c,U238} + r_{Pu/U}(t)\sigma_{a,Pu/U})e^{\sigma_{a,Pu/U}\Phi(t+\Delta t)} - \sigma_{c,U238}}{\sigma_{a,Pu/U}} \quad (3)$$

where:

$$\sigma_{a,Pu/U} = \sigma_{a,U238} - \sigma_{a,Pu239}. \quad (4)$$

The derivation of Eq. (3) is given in Appendix A.

The pin-by-pin ΔBu and $r_{Pu/U}$ distributions are computed with the flux solutions from the Pij solver.

Eq. (1) has been obtained empirically and the C_i coefficients are determined with a least squares best fit of the results of an APOLLO2-A depletion calculation of the single assembly with the device inserted.

2. Description of the Procedure

The procedure to compute the change of the pin power distribution and to update the history is:

A. Interpolate the pin cross sections and Pij data from the libraries using Eq. (1) with $\Delta Bu = 0$ and $p_{hist} = 0$, and compute an approximate two-group flux representative of the calculation done by APOLLO2-A.

B. Interpolate the cross sections and Pij data using Eq. (1) with the current values of ΔBu and p_{hist} (at the

beginning of life they are 0), and compute an approximate two-group flux representative of the real conditions.

C. Update the input data for the dehomogenization using the difference of the above two flux distributions and the $\kappa\Sigma_f$ difference from the above interpolations.

D. Apply the dehomogenization process using the updated data.

E. Integrate in time the pin-by-pin delta flux and flux in order to obtain a ΔBu and a p_{hist} distribution.

The ΔBu and p_{hist} distributions computed at step E are used as interpolation parameters for steps A and B during the next dehomogenization calculation.

III. RESULTS

Tests have been performed on colorset configurations for UOX and for MOX assemblies with the sustained insertion of a control rod. The depletion with ARTEMIS™ has been compared with a reference depletion performed with APOLLO2-A. The configurations are composed of 4 assemblies of the same type (UOX or MOX) where one of them can be controlled during the depletion, as shown in Fig. 2.

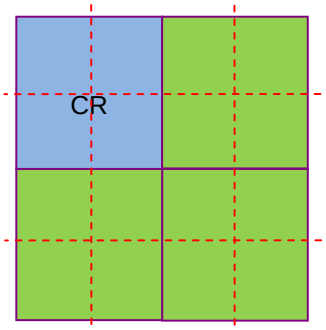

Fig. 2. Layout of the colorset with the identification of the controlled position. In dashed read are shown the symmetry axes.

The control rod is inserted and withdrawn during periods of 2.4 GWd/T. The depletions have been performed with steps of 0.2 GWd/T. The outline of the depletions is presented in Fig. 3.

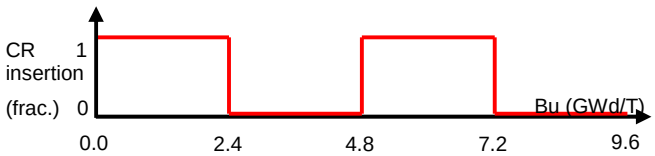

Fig. 3. Layout of the insertion-withdrawal sequence of the control rod in one assembly of the 4×4 colorset.

1. Insertion and withdrawal of a control rod in a UOX colorset

This colorset is composed of UOX assemblies with 3.0% ^{235}U enrichment. The control rod is AIC. The comparison between an ARTEMIS™ and APOLLO2-A depletion point (7.2 GWd/T) immediately before and after the withdrawal is shown in Fig. 4 and 5 and Table I, where the error is defined as (ARTEMIS™ - APOLLO2-A)/APOLLO2-A. It can be seen that the application of the LHM shows improvement. The error due to the neglected history is maximal at 7.2 GWd/T. In this case, after the withdrawal, the reference power peak is 1.064. The ARTEMIS™ result without LHM is 1.049, whereas with the LHM is 1.054, which means that the error (underestimation) is reduced from -1.4% to -0.9%.

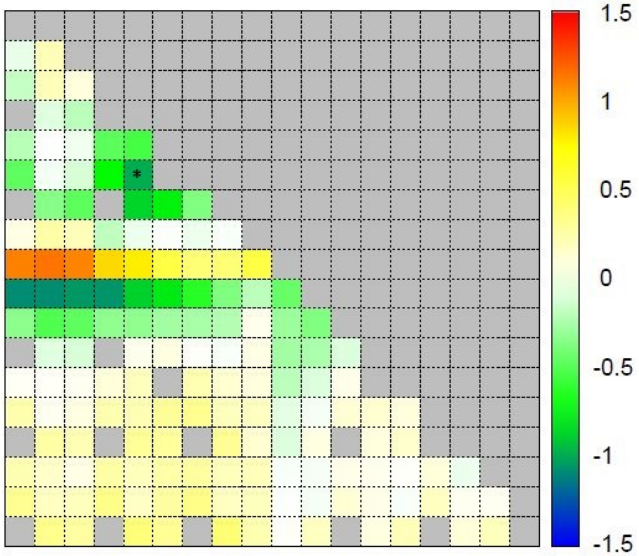

Fig. 4. Comparison between the error (%) on pin power in the UOX colorset, without LHM at 7.2 GWd/T after the withdrawal of the control rod. The peak is denoted by *.

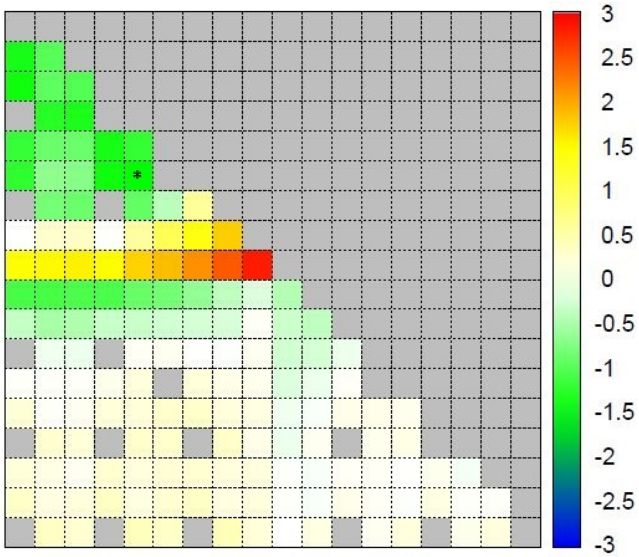

Fig. 5. Comparison between the error (%) on pin power in the UOX colorset, with LHM at 7.2 GWd/T after the withdrawal of the control rod. The peak is denoted by *.

2. Insertion and withdrawal of a control rod in a MOX colorset

This colorset is composed of MOX assemblies with 12.1, 8.2 and 4.6% Pu content disposed in three zones. The control rod is AIC. In this configuration the error is lower than the one observed in the UOX colorset. This is explained by the fact that a part of the error is due to the spectral hardening caused by the control rod. This hardening is lower in the MOX colorset, because the spectrum is already very hard, if compared to the spectrum in UOX. Nevertheless a slight improvement is brought by the application of the LHM. As in the previous case, the error due to the neglected history is maximal at 7.2 GWd/T, where the maximal error changes from 1.94% to 1.78%. In this case, after the withdrawal, the reference power pic is 1.194. The ARTEMIS^{TM} result without and with LHM is 1.196, which means in both cases an error (overestimation) of 0.2%.

Table I. Comparison between the error on pin power in the UOX colorset, without and with LHM at 7.2 GWd/T before and after the withdrawal of the control rod.

	Before withdrawal		After withdrawal	
	No LHM	LHM	No LHM	LHM
Min. diff.	-3.42	-1.94	-1.47	-0.99
Max. diff.	5.51	3.34	2.81	1.15
Avg. diff.	-0.50	-0.28	0.03	0.02
Std. dev.	2.55	1.52	1.32	0.53

IV. CONCLUSIONS

The tests on colorsets have shown that the LHM brings benefit in UOX configurations, where the history spectral effect of the control rod is not hidden by hard spectrum, as it is the case with MOX. An underestimation on the pic of -1.4% is reduced to -0.9% and the standard deviation is reduced in the worst case from 1.3% to 0.5%. In case of MOX, the error is lower and of the same magnitude order of the one committed by the DHO module in case local history effects are not present. In this case the LHM improves only slightly the pin power reconstruction.

APPENDIX A: EVOLUTION OF THE PU239/U238 RATIO

The depletion of ^{238}U and ^{239}Pu is governed by the following differential equation set:

$$\begin{aligned} &\partial_t N_{\mathrm{U238}}(t) = -N_{\mathrm{U238}}\sigma_{a,\mathrm{U238}}\Phi, \\ &\partial_t N_{\mathrm{Pu239}}(t) = \\ &\quad -N_{\mathrm{Pu239}}\sigma_{a,\mathrm{Pu239}}\Phi + N_{\mathrm{U238}}\sigma_{c,\mathrm{U238}}\Phi, \end{aligned} \tag{A.1}$$

where N_{U238} and N_{Pu239} are the nuclide densities of ^{238}U and ^{239}Pu, $\sigma_{c,\mathrm{U238}}$ is the capture cross section of ^{238}U, $\sigma_{a,\mathrm{U238}}$ and $\sigma_{a,\mathrm{Pu239}}$ are the absorption (capture plus fission) cross sections of ^{238}U and ^{239}Pu, respectively.

We define with the variable $r_{Pu/U}$ the ratio between the densities of ^{239}Pu and ^{238}U:

$$r_{Pu/U}(t) = \frac{N_{\mathrm{Pu239}}}{N_{\mathrm{U238}}}. \tag{A.2}$$

Its derivative can be expressed as:

$$\partial_t r_{Pu/U}(t) = \frac{\partial_t N_{\mathrm{Pu239}}}{N_{\mathrm{U238}}} - \frac{N_{\mathrm{Pu239}}\partial_t N_{\mathrm{U238}}}{N_{\mathrm{U238}}^2}. \tag{A.3}$$

If we insert Eqs. (A.1) and (A.2) into Eq. (A.3) and make the following definition:

$$\sigma_{a,Pu/U} = \sigma_{a,\mathrm{U238}} - \sigma_{a,\mathrm{Pu239}} \tag{A.4}$$

we obtain the following differential equation:

$$\partial_t r_{Pu/U}(t) = \sigma_{a,Pu/U}\Phi r_{Pu/U} + \sigma_{c,\mathrm{U238}}\Phi \tag{A.5}$$

whose solution is:

$$r_{Pu/U}(t+\Delta t) = \frac{(\sigma_{c,U238} + r_{Pu/U}(t)\sigma_{a,Pu/U})\mathrm{e}^{\sigma_{a,Pu/U}\Phi(t+\Delta t)} - \sigma_{c,U238}}{\sigma_{a,Pu/U}} \tag{A.6}$$

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