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HELIOS/AFEN Pin Power Reconstruction Based on Modulation Method with Group Dependent Power Form Function

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Abstract

The energy group dependent power form function has been developed for pin power reconstruction for the MOX fuel assembly. The HELIOS/AFEN pin power reconstruction procedure, based on the single assembly calculation for group dependent power form function and nodal group constants generation, has been verified against two mock-ups (ALL-MOX and GD-MOX) of PWR critical experiments loaded with high plutonium content MOX fuels. The AFEN reconstructed pin powers in MOX and UO_2 fuel assemblies are in good agreement with the experiments; the RMS error is about 1.7% for the MOX assembly of both mock-ups, which is comparable to 1.9% for the UO_2 fuel assembly. This result assures the quality of HELIOS/AFEN procedure in accurately calculating the pin power distribution in PWR core intermixed with high plutonium content MOX and UO_2 fuel assemblies.

I. Introduction

The analysis of a PWR core intermixed with MOX and UO_2 fuel assemblies requires improvement of the conventional core nuclear analysis system in the capability to accurately predict the pin power distribution under rapidly changing spatial variations of the spectrum. We have developed and verified the HELIOS/AFEN pin power reconstruction procedure, based on the modulation method with group dependent power form function from single assembly calculation, for this purpose.[1]

For practical use, it is also very important to verify the capability of calculating accurate spatial power distribution against representative critical experiments. There is little practical experimental data available, one of which being VENUS PWR critical experiments (VENUS International Program: VIP).[2] Since the current extended burnup fuel cycle scheme requires high enrichment in UO_2 fuel and/or a high plutonium content of MOX fuel, VENUS PWR critical experiments can provide additional merit in this regard: the critical mock-ups were configured with high plutonium content MOX fuels.

Thus we focused our attention in this paper on the verification of the HELIOS/AFEN procedure in calculating pin power distribution.

II. Group Constants Generation with HELIOS for AFEN Nodal Core Calculation

The AFEN[3] nodal method for core nuclear analysis generally uses two neutron energy groups and one-node-per-assembly calculation. The two-group nodal constants are the cross-sections for each reaction type, the heterogeneity factors both for the side and the corner of the fuel assembly. Since a nodal solution generally gives only the smoothly varying homogeneous flux distribution in a homogenized node, the other parameter to describe the spatially heterogeneous effect of the fuel assembly, so called form function, is additionally required from a single assembly HELIOS[4] calculation in order to reconstruct the pin power distribution of the core. Even though the HELIOS color-set model may generate more appropriate lattice constants, difficulties are expected to occur during practical application; a large number of color-set calculations are required for real core geometry due to a large number of possible fuel loading patterns for each reload cycle. So the single assembly calculation is adopted as the standard procedure of HELIOS/AFEN core nuclear analysis. The group independent power form function is used in the current pin power reconstruction procedure.

Figure 1 shows the schematic core configuration of the experiments which consisted of a test region and surrounding UO_2 fuel driver regions. In the ALL-MOX mock-up core, a standard MOX assembly was loaded at the center of the core which was surrounded by four UO_2 fuel assemblies. In the GD-MOX mock-up core, the central MOX assembly was replaced with a GD-MOX fuel assembly. Therefore, the only difference between the ALL-MOX and GD-MOX mock-up was the existence of 20 gadolinia rods, Gd_2O_3 beared in UO_2, in the central assembly, which made the critical water level higher. The HELIOS lattice calculations have used the 34-neutron-energy-group library for the typical assembly configurations of the critical mock-ups shown in Figure 2.

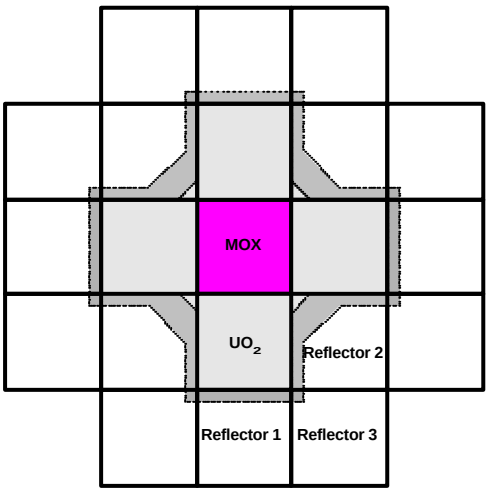


Figure 1. Spatial node division used in AFEN nodal calculation.

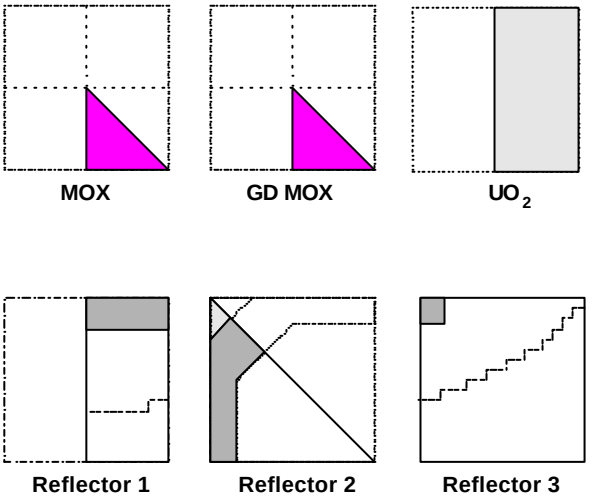


Figure 2. Configurations used in the homogenization calculations with HELIOS

III. AFEN Nodal Core Calculation

The AFEN method, developed to overcome the limitations caused by the transverse integration which are employed in most of the modern nodal methods, directly solves the multidimensional diffusion equation instead of the transverse-integrated one-dimensional diffusion. The direct solution is made possible by expanding the neutron flux in a node in terms of analytic basis functions satisfying the diffusion equation at any point of the node. The flux expansion contains non-separable cross-terms coupled to two spatial directions. The coefficients of these cross-terms are determined by the nodal corner-point fluxes which are taken as nodal unknowns in the AFEN method additionally to those in the conventional nodal methods such as the node average and the interface fluxes.

The AFEN method has shown its ability and accuracy in the nodal calculation of the core loaded with MOX assemblies through several benchmark tests.[5,6] The AFEN method owes its success in calculating the MOX loaded core to the fact that non-separable analytic function expansion of the intra-nodal flux distribution makes it possible to accurately model large localized thermal flux gradients occurring near the UO_2/MOX material discontinuity.

Encouraged by the success of these benchmark tests, we have launched a more practical verification of the HELIOS/AFEN system against two mock-ups of the VENUS PWR critical experiments which involve relatively high plutonium content MOX fuel assemblies. The core calculations were carried out with the X-Y core model in two energy groups having a relatively large node size (one-node-per-assembly). Figure 1 shows the configuration of the spatial node used in the AFEN nodal core calculation. The effective multiplication factors calculated by the AFEN are close to criticality : 0.26% and 0.30% greater than criticality for ALL-MOX and GD-MOX mock-ups, respectively.

IV. Pin Power Reconstruction with Group Independent Form Function

Since the nodal solution generally only gives the smoothly varying homogeneous flux distribution in a homogenized node, the other parameter to describe the spatially heterogeneous effect of fuel assembly, so called form function, is additionally required for pin power reconstruction. If we calculate the heterogeneous pin power by using a group independent power form function employed in the current pin power reconstruction procedure, the heterogeneous pin power is given by

$$P_{RG}^{het}(r) = (k\bar{\Sigma}_{f1} f_{1,RG}^{\hom}(r) + k\bar{\Sigma}_{f2} f_{2,RG}^{\hom}(r)) F_{SG}^{het}(r)\,, \qquad (1)$$

where, subscript "*RG*", "*SG*", "*het*", and "*hom*" stand for real geometry (e.g. reactor core configuration), spectral geometry, heterogeneous, and homogeneous, respectively. $F_{SG}^{het}(r)$ is the group independent power form function at the position $\boldsymbol{r}$ in the spectral assembly geometry defined by

$$F_{SG}^{het}(r) = \frac{k\Sigma_{f1}^{het}(r) f_{1,SG}^{het}(r) + k\Sigma_{f2}^{het}(r) f_{2,SG}^{het}(r)}{k\bar{\Sigma}_{f1}(r) f_{1,SG}^{\hom}(r) + k\bar{\Sigma}_{f2}(r) f_{2,SG}^{\hom}(r)}\,. \qquad (2)$$

Then the pin power distribution is determined by multiplying Eq.(2) to the homogeneous intra-nodal power distribution calculated with AFEN. The pin power distributions of MOX and UO_2 fuel assemblies for ALL-MOX and GD-MOX mock-ups are shown in Figures 3 and 4. The RMS errors of pin powers for MOX assemblies are 2.15% for ALL-MOX mock-up, and 3.63% for GD-MOX mock-up which are higher than 1.8% for UO_2 fuel assembly. Especially in the case of a GD-MOX core, the maximum error of 16.4% in pin power occurs at the position of gadolinia near the MOX/UO_2 interface where the neutron spectrum changes strongly.

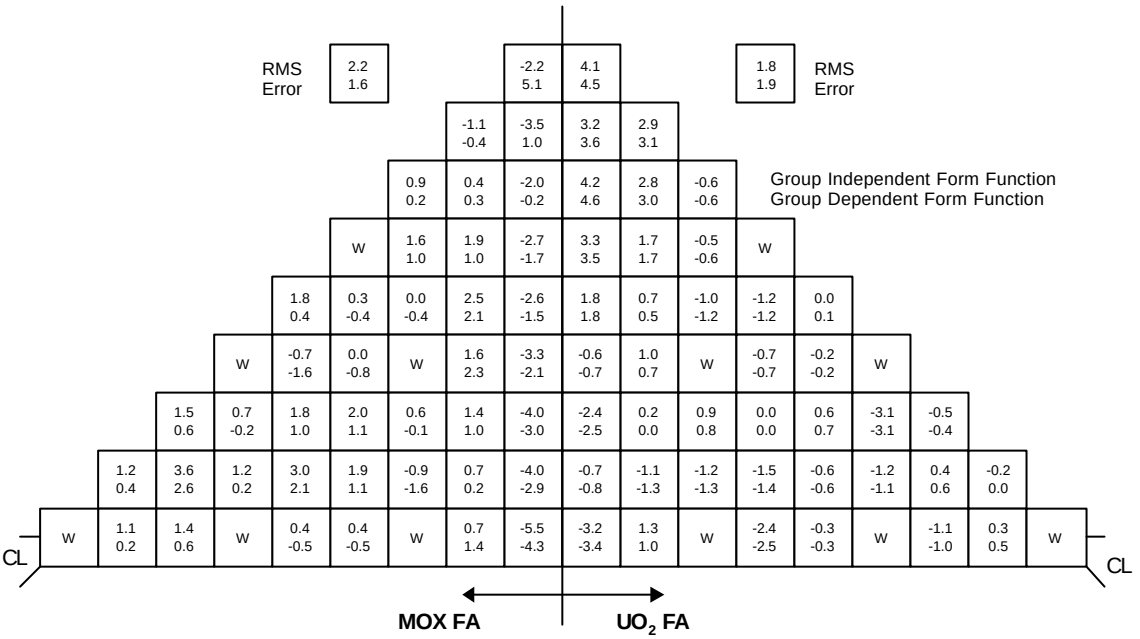


Figure 3. Error of pin power distribution calculated with AFEN, ALL-MOX core

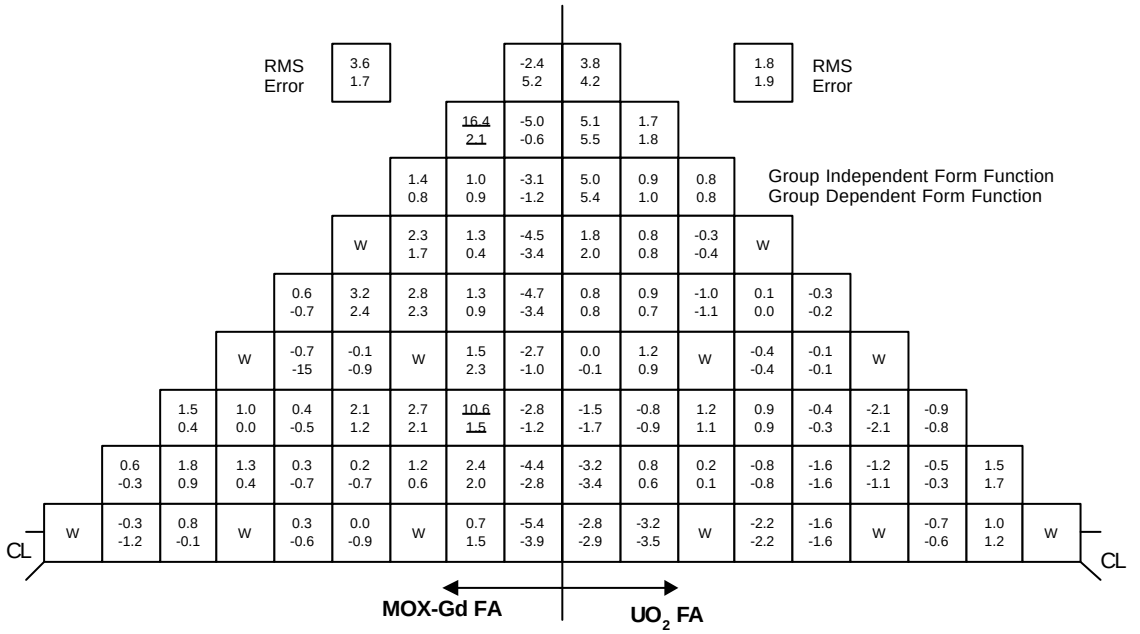


Figure 4. Error of pin power distribution calculated with AFEN, GD-MOX core
(Under bar represents the gadolinia position.)

V. Modified Pin Power Reconstruction with Group Dependent Form Function

The results of pin power modulation with a group independent form function suggest that the group dependent power form function should be applied to the modulation. The heterogeneous pin power in two-neutron-energy groups can be expressed as following;

$$P_{RG}^{het}(r) = k\Sigma_{f1}^{het}(r)f_{1,RG}^{het}(r) + k\Sigma_{f2}^{het}(r)f_{2,RG}^{het}(r) \tag{3}$$

$$= k\overline{\Sigma}_{f1}f_{1,RG}^{\hom}(r)\times\frac{k\Sigma_{f1}^{het}(r)f_{1,RG}^{het}(r)}{k\overline{\Sigma}_{f1}f_{1,RG}^{\hom}(r)} + k\overline{\Sigma}_{f2}f_{2,RG}^{\hom}(r)\times\frac{k\Sigma_{f2}^{het}(r)f_{2,RG}^{het}(r)}{k\overline{\Sigma}_{f2}f_{2,RG}^{\hom}(r)}.$$

We define $\frac{k\Sigma_{fg}^{het}(r)f_{g,RG}^{het}(r)}{k\overline{\Sigma}_{fg}f_{g,RG}^{\hom}(r)}$ as the group dependent power form function, $F_{g,RG}^{het}(r)$. In the practical application, $F_{g,RG}^{het}(r)$ can not be known unless we not only perform a nodal homogeneous but also a fine mesh heterogeneous calculation for the real geometry. This contradiction requires us to approximate the form function in the real geometry, $F_{g,RG}^{het}(r)$, to that in the spectral geometry subscribed with "*SG*" which is given by

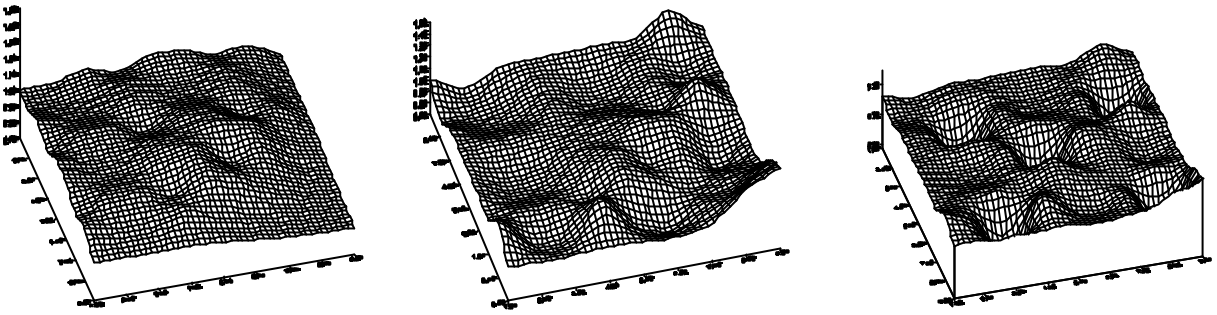
$$F_{g,SG}^{het}(r) = \frac{k\Sigma_{fg}^{het}(r)f_{g,SG}^{het}(r)}{k\overline{\Sigma}_{fg}f_{g,SG}^{\hom}(r)}. \tag{4}$$

Then, the heterogeneous pin power in two-neutron-energy groups can be expressed as

$$P_{RG}^{het}(r) = k\overline{\Sigma}_{f1,SG}f_{1,RG}^{\hom}(r)F_{1,SG}^{het}(r) + k\overline{\Sigma}_{f2,SG}f_{2,RG}^{\hom}(r)F_{2,SG}^{het}(r). \tag{5}$$

Eq.(2) and Eq.(5), the expressions for the heterogeneous pin power, becomes identical under any of the following two conditions; the power form function for both groups are nearly same, i.e., $\frac{k\Sigma_{f1}^{het}(r)f_{1,SG}^{het}(r)}{k\overline{\Sigma}_{f1}f_{1,SG}^{\hom}(r)} \approx \frac{k\Sigma_{f2}^{het}(r)f_{2,SG}^{het}(r)}{k\overline{\Sigma}_{f2}f_{2,SG}^{\hom}(r)}$, or the fission rate of a group is much larger than that of the other group, i.e., $k\Sigma_{f1}(r)f_1(r) << k\Sigma_{f2}(r)f_2(r)$ (or $k\Sigma_{f1}(r)f_1(r) >> k\Sigma_{f2}(r)f_2(r)$) in Eq.(2).

The nodal calculation for the VENUS experiments reveals that the average of the thermal to fast fission rate ratio ($k\overline{\Sigma}_{f2}\overline{f}_{2,RG}^{\hom} / k\overline{\Sigma}_{f1}\overline{f}_{1,RG}^{\hom}$) are about 4.0 for an UO_2 fuel assembly and 1.2 for a MOX fuel assembly. Because the ratio of thermal to fast group power form function is nearly uniform as shown in Figure 5 and the thermal fission rate is dominant, the pin power reconstruction with the



a) UO_2 fuel assembly b) MOX fuel assembly c) MOX-Gd fuel assembly

Figure 5. The ratio of thermal to fast group power form function for each fuel assembly. (The above figures represent a quarter of an assembly. Left-upper and right-lower corners are the center and the corner of fuel assembly.)

group independent form function results in accurate reconstructed pin powers in the UO_2 fuel assembly. However, in a MOX fuel assembly the spatial variation of the ratio is quite large as shown in Figure 5, and the average of the thermal to fast fission rate ratio is only 1.2. This observation explains why the reconstructed pin power distribution in a MOX fuel assembly with a group independent form function was not as accurate as in the UO_2 fuel assembly. In fact, the same conclusions can be extended for the highly absorbing assembly such as a heavily poisoned fuel assembly with burnable poison or control rods. Employment of an energy group dependent power form function is expected to improve the accuracy in predicting the pin-wise power distribution for both mock-ups.

The reconstruction of the pin power distribution in the revised procedure was accomplished by multiplying Eq.(5) instead of Eq.(2) to the homogeneous intra-nodal power distribution calculated with AFEN. The resulting pin power distributions of the MOX and UO_2 fuel assemblies for ALL-MOX and GD-MOX mock-ups are shown in Figures 3 and 4, which are much better than those with a group independent form function. The RMS errors of pin powers for MOX assemblies are reduced from 2.14% to 1.61% for ALL-MOX mock-up, and from 3.63% to 1.74% for GD-MOX mock-up. In the case of the GD-MOX mock-up, the pin power errors at the positions of gadolinia rods near the MOX/UO_2 interface are remarkably reduced from 16.4% to 2.1% and from 10.6% to 1.5%. This clearly shows that the assumption implied in using the group independent power form factor can not be retained for the fuel pins undergoing a significant spectrum change. The reconstructed pin power distributions in the MOX and UO_2 fuel assemblies are in good agreement with the experiments in general, in spite of the relatively high errors in the first row of fuel pins along the interface between the MOX and UO_2 fuel assemblies, which typically appear in the modulation methods for reconstructing pin power from the nodal calculation. The high errors near the interface are attributed to the use of form functions from the single assembly calculation and may be improved by using a

more realistic spectral geometry such as a color-set geometry composed of several neighboring assemblies.

VI. Conclusion

The HELIOS/AFEN pin power reconstruction procedure, based on modulation method with group dependent power form function from a single assembly calculation, has been developed and verified against two mock-ups (ALL-MOX and GD-MOX) of PWR critical experiments loaded with high plutonium content MOX fuels.

HELIOS/AFEN's reconstructed pin powers in MOX and UO_2 fuel assemblies are in good agreement with the experiments; the RMS error is about 1.7% for the MOX assembly of both mock-ups, which is comparable to 1.9% for the UO_2 fuel assembly.

This result assures the capability of the HELIOS/AFEN system in accurately calculating the pin power distribution in the PWR core intermixed with high plutonium content MOX and UO_2 fuel assemblies.

Acknowledgment

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