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Qualification of the New Pin Power Recovery Methodology

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Qualification of the New Pin Power Recovery Methodology

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1 INTRODUCTION

This report is an addendum to the qualification topical (Reference 1) of the Westinghouse Advanced Nodal Computer code, ANC, and presents ANC results using an improved methodology for the fuel pin power recovery. For convenience, this improved fuel pin power recovery methodology will be referred to in this report as "new methodology" while the existing methodology will be referred to as "conventional methodology". In addition, pin used in this report stands for the homogenized area of the cell comprised of the fuel rod, clad, and associated moderator.

As documented in WCAP-10965-P-A-AD1 (Reference 2), the conventional methodology implemented in ANC calculates the homogeneous pin power distribution and applies the group-wise pin power form factors (these were referred to as "pin factors" in Reference 2) to obtain the final pin power. The conventional methodology has shown historically that it can predict the pin power with high accuracy for traditional PWR cores, which are operated without significant insertion of control rod banks. With the introduction of new PWR core designs control rods may be inserted into the core during operation, which may significantly change the heterogeneity of the fuel assemblies. Since the conventional methodology used in ANC does not include the control rod history effect on the pin factors, the pin power distribution is not as accurate when control rods are inserted for significant periods of time during operation. This is particularly true for high-worth control rods. Moreover, because the control rod insertion and withdrawal strategy is not pre-determined, conventional pin power methodology has difficulty in capturing the heterogeneity change and the accumulated history impact on the pin power distribution. This limitation is overcome by the new methodology, which directly follows the history of each individual fuel rod in ANC and computes the fuel rod macroscopic cross-sections based on the fuel rod history and the local spectrum. Therefore, the new methodology enables ANC to calculate the effect of control rod insertion during operation on pin power distribution while maintaining the same accuracy as the conventional method for a traditional core.

The new methodology has been implemented in a version of ANC, which uses the NEXUS cross-section representation (Reference 3). This new pin power methodology has been qualified by comparisons of pin powers from single assembly ANC calculations to corresponding pin powers calculated by the pin by pin transport theory lattice code PARAGON (Reference 4) at identical conditions. A wide range of control rod insertion and withdrawal scenarios was used for these comparisons including very challenging control rod history cases beyond those anticipated at actual core operating conditions. The comparisons cover a burnup range well beyond the current limit on fuel rod-average burnup of 62 GWD/MTU.

In addition to the single assembly control rod history scenarios described above, comparison of results between the new and conventional pin power methodology for traditional unrodded PWR core simulations demonstrates that the new method is as accurate as the conventional method for unrodded cases. Pin power comparisons for selected pins as well as the detailed pin power distributions are presented in this report. Unless otherwise noted, the percent pin power differences shown in this report are calculated as the delta pin power in ANC minus the corresponding PARAGON value multiplied by 100. The assembly average pin power differences are the root mean square differences multiplied by 100 between ANC and PARAGON.

2 METHODOLOGY

The new methodology described in this report represents an evolution in pin power recovery methodology for current nodal codes. With the conventional methodology, in order to take into account the history effect of control rod insertion and withdrawal, the pin power form factors are pre-generated as a function of additional history parameters (e.g., coolant density history and control rod history, etc.). Typically, these history cases involve straight-forward lattice depletion calculations with the given history parameter kept constant for each history case. While control rod history is often modeled in this way (i.e. the control rod is continually inserted for a control rod history case), it is not representative of actual in-core control rod operation where repeated insertion and withdrawal of control rods for any given computational node in the nodal core model can be expected. Furthermore, application of these control rod history data requires very complicated procedures to track and combine the various periods of control rod insertion and withdrawal in each node that has been subjected to such sequences.

The following terminologies are used in this report:

[ ]a, c, f

The conventional pin power methodology does not directly account for the real depletion history of each individual fuel pin, thereby limiting its predicting capabilities in strongly heterogeneous environments not specifically calculated during cross-section generation, such as those characterized by repeated insertion of control rods. This limitation is overcome by the new pin power methodology described in this report.

The conventional pin power equation can be written as the following:

$$P^k = \sum_g \kappa\Sigma_{f,g}^{\mathrm{hom},k} \cdot \phi_g^{\mathrm{hom},k} \cdot p_g^k$$

[ ]a, c, f

[ ]a, c, f

Or

[ ]a, c, f (1)

[ ]a, c, f

All the correction factors are pre-obtained and tabulated for each cross-section type through a set of lattice code depletion and branch calculations at various conditions to force significant differences in neutron spectrum and calculate their incremental effect.

The homogeneous flux distribution calculation remains the same as in the conventional methodology (Reference 2), i.e., it is obtained by solving the coupled diffusion equation to meet the boundary conditions of surface and corner fluxes for each node.

[

]$^{a, c, f}$

The pin power is finally computed using equation (1) with the pin flux form factors and macroscopic cross-sections calculated as discussed above.

3 NEW PIN POWER METHODOLOGY QUALIFICATION

3.1 SINGLE ASSEMBLY MODEL CALCULATIONS

3.1.1 Single Assembly Calculations for non-BA Assemblies

The fuel assembly design used in this set of simulations is standard 17x17 Westinghouse fuel with 4.95 w/o ^{235}U. The pin map is displayed in Figure 1. Four control rod history sequences were simulated, as shown in Figure 2. Various control rod materials were modeled during the qualification. The reference results for each sequence are obtained from calculations using PARAGON, which is able to calculate explicitly the actual pin-by-pin fuel depletion. The PARAGON pin-by-pin power results are then compared against ANC using the new pin power methodology. It is concluded from the comparisons that the accuracy of the new pin power methodology shows no dependence on the control rod type. Also, results are consistent for all the simulated control sequences. As an example, the results from sequence 2 for 24 Ag-In-Cd control rodlets are displayed in this report. This scenario results in a severe heterogeneity change for the assembly and therefore yields challenging conditions to the new methodology.

The maximum pin power error is shown for the corner pin and for pin (5,4), which is close to the guide thimble, or control rod at rodded conditions. The corner pin is shown since the power migrates to the corner as a consequence of control rod insertion. Pin (5,4) is of interest since the power redistributes and typically peaks at (5,4) when the control rods are extracted.

The pin power differences between ANC and PARAGON are shown as a function of burnup in Figure 3 for the 4.95 w/o ^{235}U fuel. Figure 3 shows the agreement for the pins at the corner (top-left plot) and in location (5,4) (top-right plot), as well as the limiting pin of the assembly (bottom-left). The agreement for these pins with the new methodology is typically within [ ]^{a,c} and practically always within [ ]^{a,c} at high burnups. The average pin power difference for the assembly (bottom-right plot), which is indicative of the overall accuracy of the methodology, shows practically no difference between the new methodology as implemented in ANC and PARAGON results. As a detailed comparison, the pin power distributions at 25 GWD/MTU, for each modeled control rod insertion sequence are given in Figure 4.

Results have been obtained for low enriched fuel, as well as the 4.95 w/o ^{235}U, demonstrate that the new methodology is accurate for the enrichment range used in PWR cores.

3.1.2 Single Assembly Calculations for BA Assemblies

Assemblies containing Burnable Absorbers (BAs) were also analyzed with several control rod insertion scenarios during this qualification. The calculations cover typical BA types, such as IFBA and WABA assemblies and assemblies with gadolinia pins. For IFBA assemblies, several IFBA pin loading patterns were modeled. The results for a 156 IFBA assembly and a gadolinia assembly for the sequence shown in Figure 7 are presented in this report. The corresponding assembly configurations are given in Figure 5 and Figure 6.

A summary of the results of the pin power comparison between ANC vs. PARAGON for the BA assemblies are given in Figure 8 through Figure 11. The results are similar to those described earlier for non-BA assemblies. The discrepancy for the limiting pin is within [ ]^{a,c} for most of the burnup range, and remains practically within [ ]^{a,c} at high burnup. The assembly average pin power discrepancy is mostly within [ ]^{a,c} for the examined burnup range, which confirms an overall remarkable agreement throughout the assembly.

Overall results for the gadolinia fuel assembly are comparable to IFBA and WABA fuel, however slightly larger assembly-average differences were observed in the first part of the depletion. The larger difference appears where the gadolinia pin power typically peaks. However, the difference is still within the uncertainty and the gadolinia pin power is still considerably lower than the limiting power pin at the time when the larger difference occurs. Moreover, the power difference of the gadolinia pin reduces significantly after the gadolinium burnout.

3.2 PWR CORE CALCULATIONS

A model for a traditional 4-loop plant without control rod insertion was generated and analyzed with the new pin power methodology and the pin power results were compared to those of the same core modeled with the conventional pin power methodology. Core summary data in Table 1 show only small differences [ ]^{a,c} in core peak F_Q, $F_{\Delta H}$ and Fz over the cycle. Detailed comparisons of assembly-wise peaking factors $F_{\Delta H}$ and F_Q at EOL, shown in Figure 12 and Figure 13 respectively, confirm good agreement between the two methodologies. The comparisons show agreement within the [ ]^{a,c} range, with the new methodology predicting slightly lower peaks for the peripheral assemblies due to the fact that the new pin power methodology can take into account the effect of the pin burnup tilt of the peripheral assemblies. It is thus concluded that there is no significant difference in pin power results for unrodded cores between the new and conventional pin power methodologies.

Figure 1 Pin Map of 17x17 non-BA Fuel Assembly

a, c

Figure 2 Control Rod Sequences Modeled for non-BA Assembly Calculations

a, c

Figure 3 Pin Power Comparisons for 4.95 w/o U235 non-BA Fuel
(ANC vs PARAGON, Sequence #2)

a,c

Figure 4 Comparison of Pin Power Distribution for 4.95 w/o U235 Fuel at 25 GWD/MTU
(ANC vs PARAGON, Sequence #2)

a, c

Figure 5 Pin Map of 156 IFBA Fuel Assembly

a, c

Figure 6 Pin Map of Gadolinia Fuel Assembly

a, c

Figure 7 Control Rod Sequences Modeled for Presented BA Assembly Calculations

a, c

Figure 8 Comparison of Pin Power for 156 IFBA Fuel Assemblies
(ANC vs PARAGON)

a,c

Figure 9 Comparison of Pin Power for Gadolinia Fuel Assembly
(ANC vs PARAGON)

a,c

Figure 10 Comparison of Pin Power Distribution for 156 IFBA Fuel Assembly
(ANC vs PARAGON at 25 GWD/MTU)

a,c

Figure 11 Comparison of Pin Power Distribution for Gadolinia Fuel Assembly
(ANC vs PARAGON at 25 GWD/MTU)

a,c

Table 1 Summary of Core Results for ANC between New and Conventional Methodology

[ ]a,c

Figure 12 Comparison of Assembly-Wise $F_{\Delta H}$ between New and Conventional Pin Power Methodology

a,c

Figure 13 Comparison of Assembly-Wise F_Q between New and Conventional Pin Power Methodology

a,c

4 SUMMARY

Westinghouse has developed a new pin power recovery methodology, which allows the nodal code to predict the fuel rod power distribution for the core operated at any condition, including control rod insertion. By following and making use of the real history of each individual fuel rod, the new pin power methodology captures both the instantaneous and historic effect of the heterogeneity change due to control rod insertion during the operation with excellent accuracy.

The new pin power methodology will be implemented in the Westinghouse nodal code ANC. Qualification of the methodology was performed through calculations of various control insertion strategies including some extreme conditions, comparing ANC pin powers to reference PARAGON results at the same conditions. These qualification calculations were performed at both high (4.95 w/o) and low enrichment over a large burnup range and included assembly designs with IFBA, WABA, and gadolinia absorbers. The results of the qualification show that for all cases the pin power differences are within [ ]^{a,c} for most of the burnup range and within [ ]^{a,c} for high burnups. Comparisons of the new methodology against the conventional pin power methodology for core calculation simulating unrodded operation shows that the excellent accuracy of the conventional methodology for this situation has been maintained.

Hence, all qualification results presented in this report demonstrate the accuracy of the new pin power methodology, and confirm that the new pin power methodology is accurate for both unrodded and rodded pin power predictions.

5 REFERENCES

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