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Analysis of the Pin Power Peaking of the Hatch Unit 1 Cycle 21 Failed Fuel Assemblies

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Abstract – *This paper documents the results of the analyses of local pin power peaking of the failed fuel assemblies, due to Pellet Clad Interaction (PCI), in Hatch Unit 1 Cycle 21. These analyses were performed with the latest CASMO5/SIMULATE5 codes utilizing the advanced neutronics and thermal hydraulic models, such as the Quarter Assembly Thermal Hydraulic (QTH) model, in an attempt to assess the impact of such detail models on the pin power peaking. CASMO5 and SIMULATE5 are Studsvik Scandpower's next generation lattice and nodal codes. The advanced features of CASMO5 and SIMULATE5 have shown to have a significant impact on the local peaking of assemblies in cells with skewed power and void profile.*

I. INTRODUCTION

The fuel failures at Hatch Unit 1 occurred during Cycle 21 toward the end of the cycle at around cycle exposure 13.29 GWD/ST as the control rods were pulled from Notch 14 to Notch 16. The failed fuel assemblies were controlled with deep control blades (notch positions 8 to 16) for approximately 2 GWD/ST prior to the failure. Six pins had failed in 4 bundles located in 3 out of 4 symmetric control cells diagonally adjacent to the control cell at the middle of the core. Almost all the failures had occurred near axial location of 105" above the lower end plug. All the failed fuel rods were on the Wide-Wide (WW) side near the Wide-Wide Corner (WWC) facing the control blade.

At the request of the Southern Nuclear Operating Company, Studsvik Scandpower, Inc has performed detailed analysis of local pin power peaking of the four failed assemblies, due to PCI, in Hatch Unit 1 Cycle 21 utilizing CASMO5/SIMULATE5 codes. CASMO5 and SIMULATE5 are Studsvik Scandpower's next generation lattice and nodal codes. The primary objective of this project was to take advantage of the SIMULATE5 detailed neutronics and thermal hydraulic models, such as the Quarter Assembly Thermal Hydraulic (QTH) model, in an attempt to assess the impact of such detailed models on the pin power peaking . Such advanced modeling features of CASMO5 and SIMULATE5 have shown to have a significant impact on local peaking of the edge pins facing the control blade in the assemblies in cells with skewed power and void profile, such as a deep controlled cell.

The analysis of the local pin power peaking for the failed fuel in Cycle 21 involved detailed multi-cycle depletion calculations with CASMO5/SIMULATE5 starting with Cycle 19 in order to properly capture the power and the burnup history of the bundles in Cycle 21. Another set of calculations for these cycles were also performed with CASMO4/SIMULATE3 and used as the reference calculations. The analysis of Cycle 21 primarily was focused on the local pin power peaking of the failed fuel assemblies in this cycle.

The effect of several different physics and modeling options within SIMULATE5, such as the QTH model, was evaluated in order to isolate the effect of such options in the local pin power peaking. In addition, separate calculations were performed with the inclusion of the channel bow model for the cells with failed fuels in Cycle 21. The data for the channel bow model was based on assumed bow of 50 and 150 mil for once and twice burned assemblies, respectively at the axial height corresponding to the location where the failure had occurred. It should be noted that the typical measured channel bow values in many of the currently operating plants may be much higher than the assumed values used in these analyses. Furthermore, it is assumed that the assembly bow is away from the blade thus creating an additional gap on the WW side. These calculations illustrate the impact of such additional gaps introduced due to the channel bow on the bundle pin power peaking. The CASMO5/SIMULATE5 results from Cycle 21 were compared against results from calculations performed with CASMO4 and SIMULATE3.

In the following sections, a brief description of the CASMO5 and SIMULATE5 code package, along with the pin power comparisons will be presented.

II. METHODOLOGY

As mentioned earlier, the primary objective of this project was to take advantage of the CASMO5/SIMULATE5 detailed neutronics and thermal hydraulic models in an attempt to assess the impact of such detailed models on the pin power peaking. CASMO5 and SIMULATE5 are Studsvik Scandpower's next generation lattice and nodal codes. Presented in the following sections is a brief overview of CASMO5 and SIMULATE5 with emphasis on the features critical to this analysis.

II.A. CASMO5

CASMO5 is a two-dimensional characteristics based neutron and gamma transport theory lattice physics code with depletion capability. CASMO5 is utilized to generate cross sections and discontinuity factors for both BWR and PWR diffusion theory 3-D nodal core analysis. CASMO5 includes many advancements both in physics modeling and capabilities. Reference 1 presents the details of CASMO5 capabilities and features. Below is a short list of some of the new features in CASMO5.

- MxN Heterogeneous Method of Characteristics
- Pn-Scattering
- Resonance upscattering
- Analytical energy release model
- Generalized racks
- Spent nuclear fuel edits
- 586 group library
  - ENDF/B-VII R0
  - >400 nuclides/materials
  - Shielded data for >100 nuclides including major fission products
  - Extensive depletion chains

II.B. SIMULATE5

SIMULATE5 is Studsvik Scandpower's new nodal code which will replace the existing SIMULATE3 code. It combines the best features of SIMULATE3 along with the new advancements in physics models, both neutronics and thermal hydraulics. Below is a brief list of new features.

- Hybrid Macroscopic/Microscopic depletion model
- General energy group fully analytic nodal model
- Axial Homogenization model
- Radial submesh 2-D re-homogenization model
- Advanced Quarter Assembly Thermal Hydraulic (QTH) model for BWRs
- Gamma scan analysis capabilities at both bundle and pin level
- Explicit modeling of intra-assembly gap variation (i.e. channel bow)
- LPRM tube modeling capability, now a standard feature

The Quarter Assembly Thermal Hydraulic (QTH) model is of the most interest to this analysis. Previous studies have shown that the QTH model had a significant impact on pin power peaking of assemblies in cells with a skewed power and void profile, such as a deep controlled cell.

The complete discussion of the SIMULATE5 features and capabilities are outside the scope of this paper; however, a brief description of the QTH model is presented to illustrate the mechanics of this model which could help in the understanding of the reasons behind its effect and importance. References 2 and 3 present the details of SIMULATE5 models and features.

The BWR thermal hydraulics module of SIMULATE5 models the entire vessel loop: core, chimney (for natural circulation reactors), upper plenum, stand pipes, steam separators, steam dome, upper and lower downcomer, re-circulation pumps, and lower plenum. Each assembly of the core is analyzed in detail. The assembly consists of a number of parallel channels (active coolant and water rod(s)), which are treated individually. In SIMULATE5, the channels within the core are divided into 'subnodes' in the same manner as in the neutronics calculations; i.e., such that each subnode is materially and geometrically uniform in the axial direction. For each subnode, requirements have to be met regarding mass balance, energy balance, and momentum balance. Basically, SIMULATE5 is a 4-equation model keeping track of total flow rate, vapor flow rate, liquid/vapor mixture enthalpy, and local pressure.

SIMULATE5 offers as an option a TH evaluation of each quarter-bundle of a BWR assembly (QTH model) as shown in Fig. 1. Cross-flow is allowed between the sub channels. SIMULATE5 first performs the TH evaluation for the full assembly in the "conventional" manner to calculate parameters such as total assembly flow rate. The results from the full assembly TH evaluation are used as boundary conditions to evaluate each quarter bundle. The power of each submesh is also readily available. The only complication is that, normally, the quarter-bundle subdivision lines cut through the submeshes as illustrated in Fig. 1. The power in a subdivided submesh is estimated by assuming that the power distribution of the submesh is represented by the second order quadratic polynomials in x and y direction where the expansion coefficients are obtained by fitting a parabola to the submesh average and side powers.

The results from the TH evaluation are fed back to the submesh neutronic calculations through density distribution. The resultant of this TH and neutronic iteration is an explicit power and void distribution for each quadrant within all the assemblies in the core. Note that in a conventional TH model employed in all nodal codes a uniform distribution of void and power is assumed across each assembly. The detailed knowledge of the void and power profiles within each assembly is vital in an accurate prediction of the pin power peaking within each bundle in each cell. This is especially true for assemblies with a deep control rod. For such cases, the power distribution is strongly tilted in the xy plane which results in a heavily skewed void and density distribution as well.

Fig. 2 presents the sub-channel void and power distribution for a test BWR assembly with a 64% inserted control rod. In such a case, the power is highly peaked towards the NN (Narrow-Narrow) corner of the assembly, and intra-bundle cross flow is computed. At the tip of the control rod, the void in the sub-channel adjacent to the rod is 14%, while it is 54% in the NN corner.

The QTH model within SIMULATE5 is an essential feature in accurately calculating the details in pin power peaking within each assembly in the core.

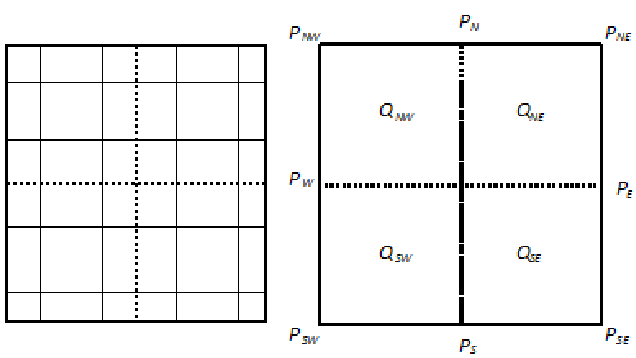

Fig. 1. SIMULATE5 Submeshes and quarter-assemblies model

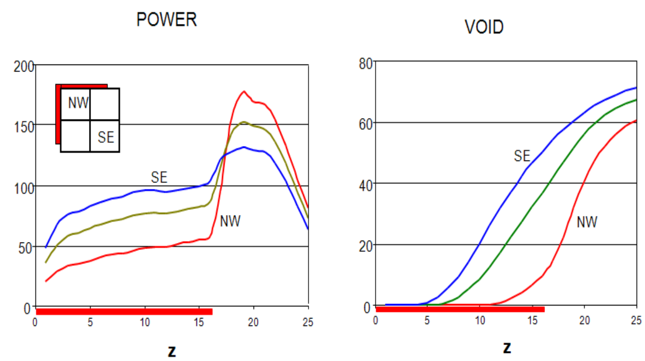

Fig. 2. SIMULATE5 power & void distribution with QTH option

SIMULATE5 is also capable of modeling of the change in inter-assembly gap size due to assembly bowing. The gap corrections are done by modifying the nodal cross-sections, discontinuity factors and pin form functions by interpolating on delta-gap branch data, which is generated with CASMO5 and tabulated in the library for the given 3D delta gap distribution. Although the bow is not typically a known quantity during a design analysis, it is valuable in performing sensitivity analyses, such as determining the uncertainty in CPR or peak kW/ft with respect to channel bow uncertainty.

III. RESULTS

A series of detailed depletion calculations were performed for Hatch Unit 1 from Cycles 19 through 21 utilizing both versions of the code and the results and the comparisons of the pin power peaking from these calculations are presented in this section. The detailed multi-cycle depletion calculations were performed starting with Cycle 19 in order to properly capture the power and the burnup history of the bundles in Cycle 21. The primary focus of the analysis was to better understand the behavior of the local pin power peaking of the failed fuel assemblies in Cycle 21 between the two codes. Also, the effect of different physics and modeling options within SIMULATE5, such as the QTH thermal hydraulic, was evaluated in order to isolate the effect of this option in the local pin power peaking. In addition, a separate CASMO5/SIMULATE5 calculation was performed with the channel bow model for the cells with failed fuel in Cycle 21. As mentioned earlier, the data for the channel bow model was based on assumed bow of 50 and 150 mils for once and twice burned assemblies, respectively at the axial height (105”) corresponding to the location where the failure had occurred. Furthermore, it is assumed that the assembly bow is away from the blade, thus creating an additional gap on the WW side as illustrated in Fig. 3.

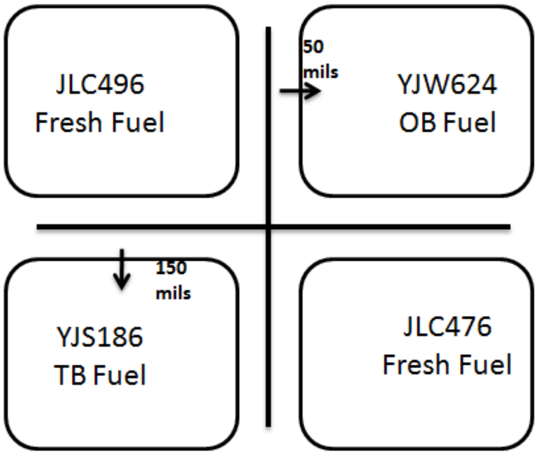

Fig. 3. Control cell with an assumed channel bow

III.A. Pin Power Comparison

With the primary focus of the analysis concentrated on the better understanding of the behavior of the local pin power peaking of the failed fuel assemblies in Cycle 21 a set of detailed depletion calculations were performed with CASMO4/SIMULATE3 and CASMO5/SIMULATE5 and the comparisons of the results at the pin power level are presented in this section. The results will illustrate the effect of the QTH model on the pin power peaking of the failed fuel rods and will provide the comparisons of results between the two codes. Also presented in this section are the results of separate calculations that were performed with the channel bow model for the cells with failed fuel in Cycle 21.

Table I presents the list of the failed fuel assemblies and the failed pins in each assembly. The four failed fuel assemblies were located in 3 out of 4 symmetric control cells diagonally adjacent to the control cell at the middle of the core. The fuel failures had occurred toward the end of cycle at ~13.29 GWD/St as the control rods were pulled out from Notch 14 to Notch 16. All the failed fuel pins were on the Wide-Wide (WW) side near the WWC facing the control rod. The failures had occurred at around 105" above the lower end plug (middle of node 18).

Table I Fuel assemblies in Hatch 1 Cycle 21

Bundle Serial #	Core Location	Failed Pins
JLC496	11,15	A3, A4, C1
JLC476	12,16	D1
JLC495	16,15	A4
JLC494	16,12	D1

The fuel pins A3, A4, C1, and D1 were the top four leading pins in power within all four failed assemblies at the exposure points when the failure occurred. Considering that the results for all these pins in the four failed assemblies were very similar, the pin power comparisons between SIMULATE3 and SIMULATE5 for only the A4 and D1 fuel rods in the failed assembly JLC496 will be presented in this section. This fresh fuel assembly, JLC496, was loaded in the lower left quadrant of the core at BOC21. There were three failed fuel pins, A3, A4, and C1 in this bundle as shown in Fig. 4.

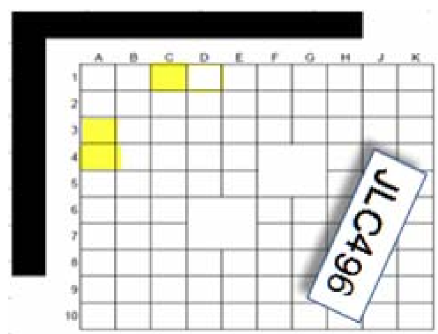

Fig. 4. Bundle JLC496 in Hatch 1 Cycle 21

Figures 5 and 6 present the comparisons of the relative pin power and KW/FT for fuel rods, A4 and D1 in bundle JLC496 at cycle exposure 13.06 GWD/ST prior to the failure.

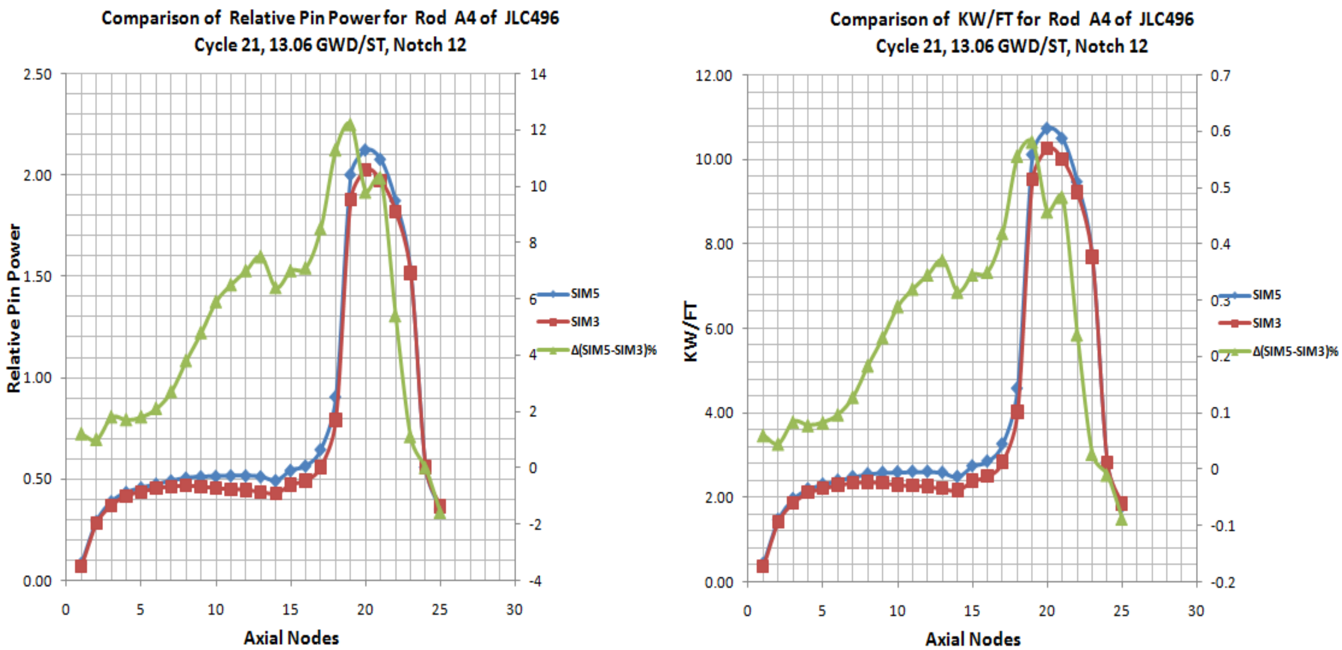

Fig. 5. Relative pin power and KW/FT (SIM5 with QTH vs. SIM3) for rod A4 of JLC496, C21 at 13.06 GWD/ST

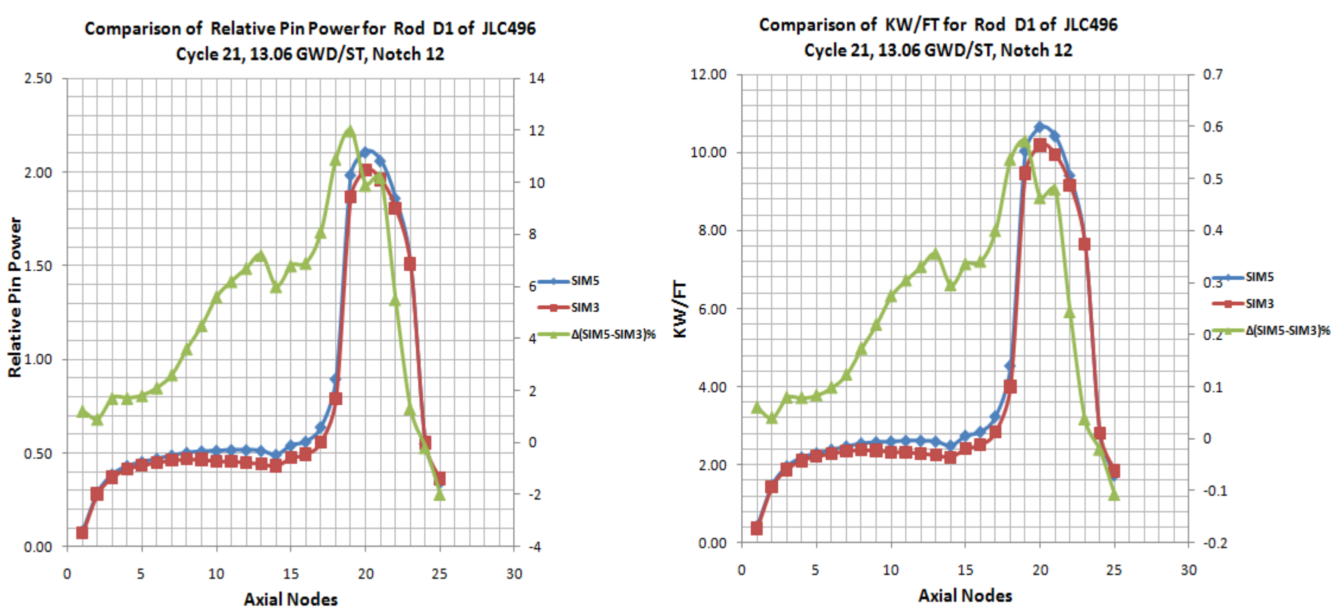

Fig. 6. Relative pin power and KW/FT (SIM5 with QTH vs. SIM3) for rod D1 of JLC496, C21 at 13.06 GWD/ST

As shown in these figures, SIMULATE3 under predicts the pin power peaking at the peak axial nodes (17-20) by about 10% compared to SIMULATE5. As expected, the 10% difference in the pin power near the peak is mostly due to the QTH model. Once the QTH model is turned off, the SIMULATE5 and SIMULATE3 differences are not as much. This is shown in Fig. 7, which is similar to Figures 5 and 6 with the exception that the comparison is made between SIMULATE5 without the QTH model and SIMULATE3. The comparison of the results illustrates that the QTH model in SIMULATE5 captures the effect of a skewed power and void profile, due to the presence of a deep control bade, on pin power peaking for the edge pins in the WW side. Although not presented here, the results of the pin power comparison for the other failed fuel pins in the other three fuel assemblies exhibits similar behavior.

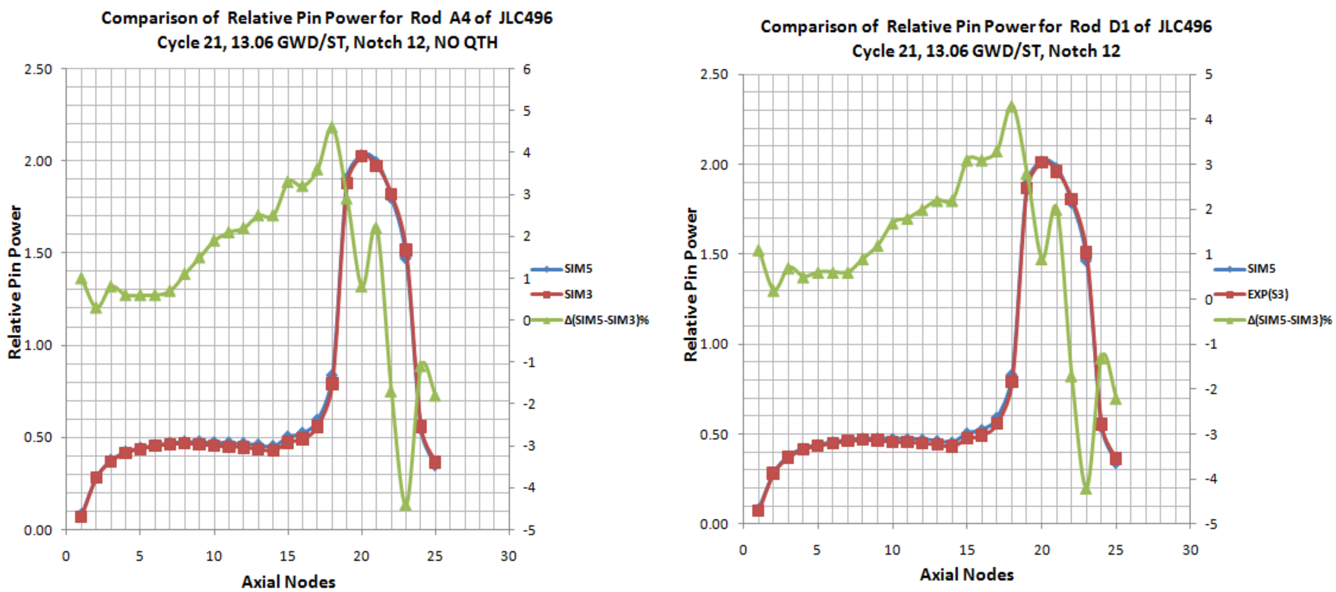

Fig. 7. Relative pin power (SIM5 without QTH vs. SIM3) for rods A4 & D1 of JLC496, C21 at 13.06 GWD/ST

III.B. Effect of channel bow on pin power peaking

The results presented in this section illustrate the effect of the channel bow model on the pin power peaking. Separate SIMULATE5 calculations were performed with the inclusion of the channel bow model for the cells with failed fuel in Cycle 21. It was assumed that the channel bow for all the bundles in the failed fuel cells was present throughout the cycle starting from BOC21, thus the cycle depletion calculations were performed with constant channel bow values for these bundles. Considering the fact that the channel bow is an exposure dependant phenomena and that the once and twice burned bundles loaded at BOC21 would have had some degree of bow, the assumption of depleting the entire cycle with the available channel bow data would be a realistic approach. Presented here are the comparisons of results from these SIMULATE5 calculations against the original "reference" SIMULATE3 calculations for fuel assembly JLC496.

Figures 8 and 9 present comparisons of relative pin power and the KW/FT for the four leading pins in bundle JLC496 at 13.06 GMWD/ST cycle exposure. Note that these figures are similar to Figures 5 and 6 with the exception that the SIMULATE5 results presented here reflect the effect of the channel bow modeled in the Cycle 21 depletion calculation. These results clearly illustrate the effect of additional gaps introduced in between the bundles in this cell due to the channel bow. As expected the addition of extra gaps between the bundles translated to an increase in pin power peaking especially for the pins near the edge of the bundle. As shown in Figures 8 and 9 the differences between SIMULATE5 and SIMULATE3 pin power jumped to about 15-17% once the channel bow effect was accounted for in the SIMULATE5 calculations. The degree of increase in pin power peaking depends on the magnitude of the excess gap introduced. It is expected that the effect of the channel bow would be highest on the pin power peaking of bundle JLC496 for the pins in the side of the assembly with the largest gap introduced by the bow on the adjacent twice- burned bundles.

Fig. 10 represents the comparison of the relative pin power and KW/FT at different axial nodes for one of the failed fuel rods (A4) in bundle JLC496. The sharp peaks around the 13 GWD/ST cycle exposure correspond to the power surge at nodes 17-20 as the control rods were pulled from notch position 12 to 16 between exposure steps. Finally, Fig. 11 shows the calculated KW/FT for rod A4 in bundle JLC496 at axial node 18 as a function of pin exposure at that node. As shown on this figure, the KW/FT for node 18 jumped from ~4 to ~11 at around ~25 GWD/ST exposure.

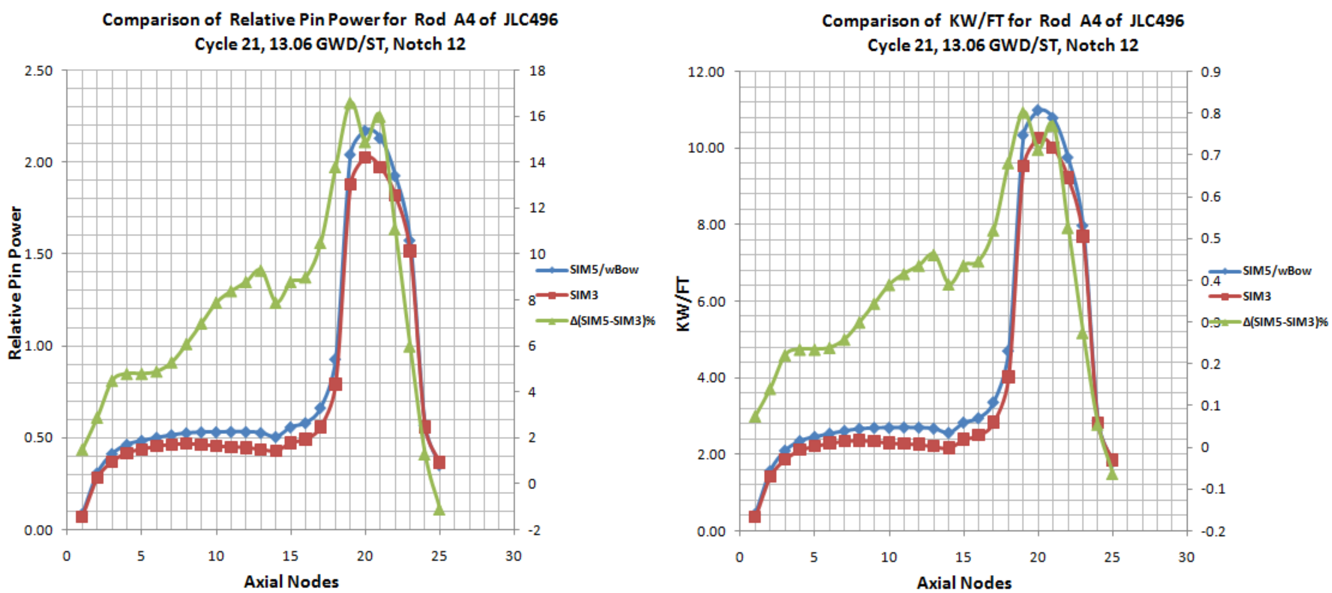

Fig. 8. Relative pin power and KW/FT (SIM5 with QTH & BOW vs. SIM3) for rod A4 of JLC496, C21 at 13.06 GWD/ST

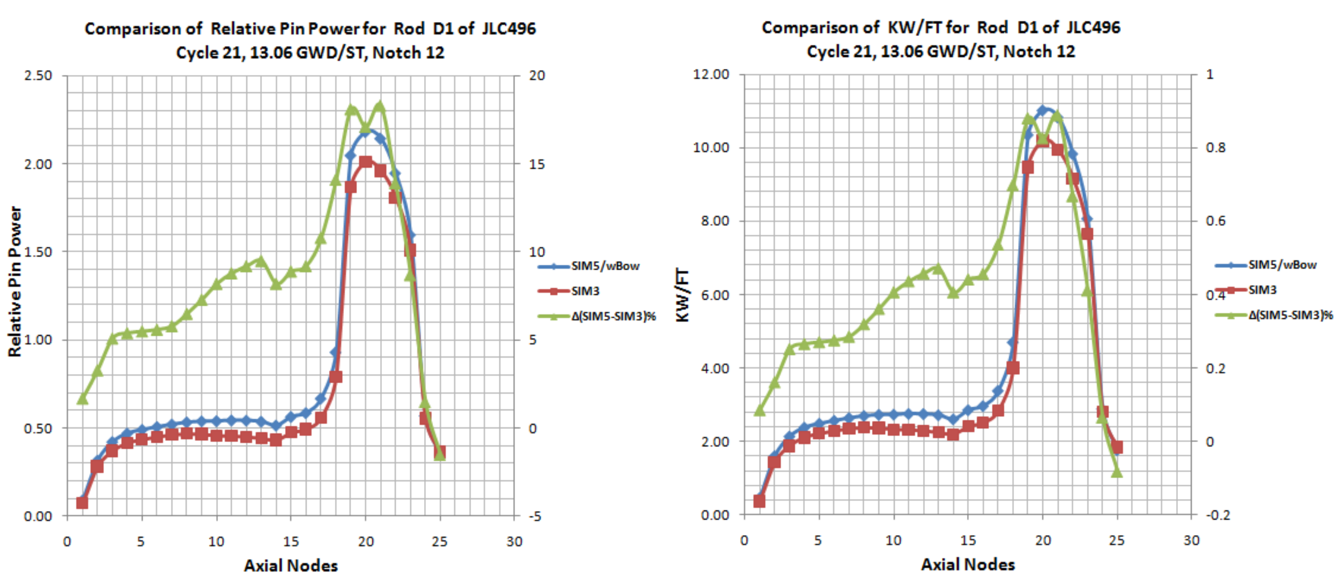

Fig. 9. Relative pin power and KW/FT (SIM5 with QTH & BOW vs. SIM3) for rod D1 of JLC496, C21 at 13.06 GWD/ST

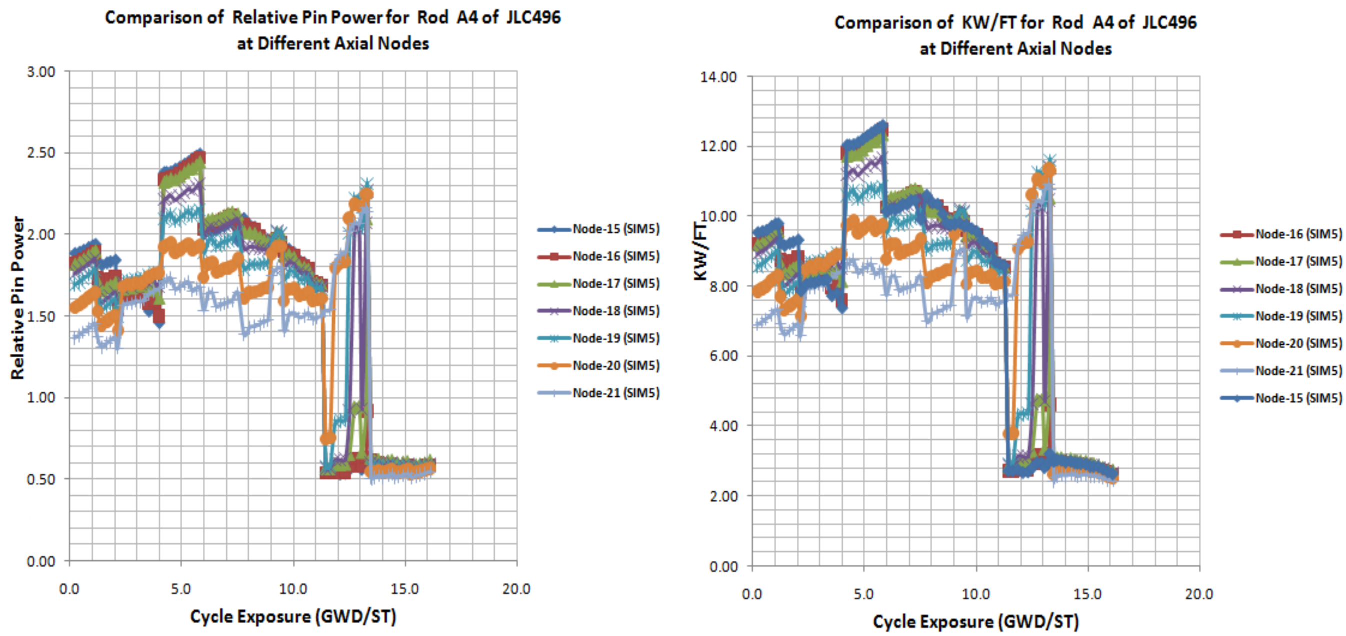

Fig. 10. SIMULATE5 calculated relative pin power and KW/FT for rod A4 of JLC496 at several axial nodes

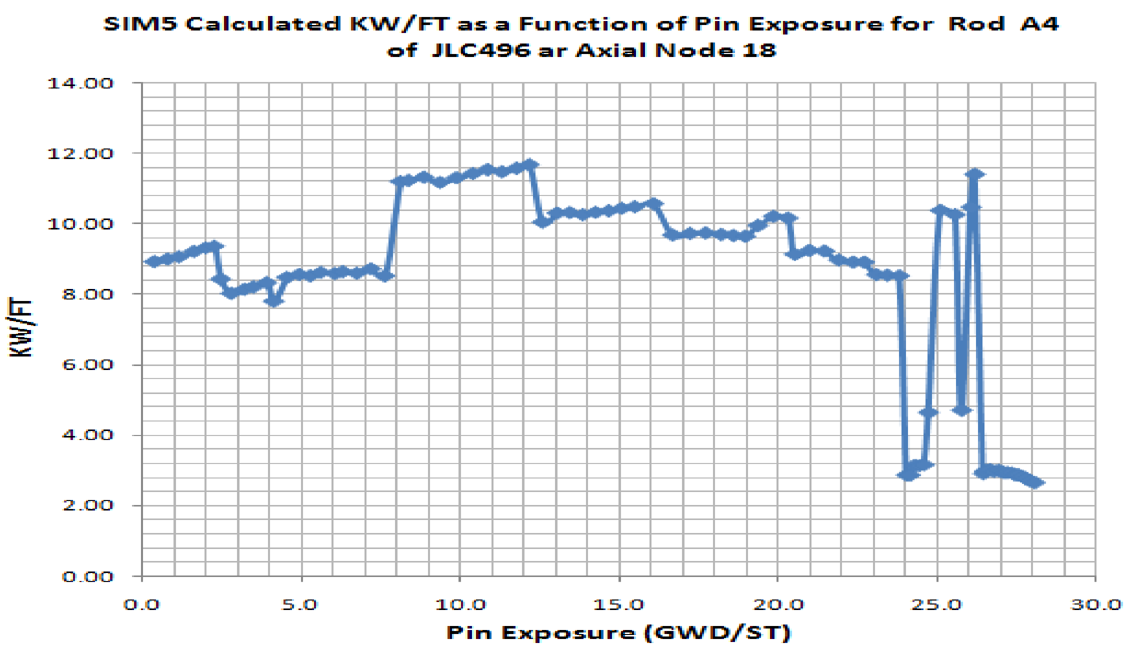

Fig. 11. SIMULATE5 calculated KW/FT for rod A4 of JLC496 at node 18

IV. CONCLUSIONS

The analyses of local pin power peaking for the failed assemblies in Hatch Unit 1 Cycle 21 with emphasis on pin power peaking comparisons was completed and the results are documented in this paper. These analyses were performed with the latest CASMO5/SIMULATE5 codes utilizing the advanced neutronics and thermal hydraulic models, such as the Quarter Assembly Thermal Hydraulic (QTH) model. The analyses focused on assessing the impact of such detailed models on the pin power peaking.

The CASMO5/SIMULATE5 analyses of Hatch 1 Cycles 19 through 21 were completed and results were compared with CASMO4/SIMULATE3 reference calculations. The primary objective of these calculations was to take advantage of the SIMULATE5 detailed physics models to better understand the pin power peaking of the failed assemblies in Hatch Unit 1 Cycle 21. The results of the analyses illustrated that the pin power peaking for the failed pins in all the failed assemblies obtained by CASMO5/SIMULATE5 with the QTH model was about 10% higher than the SIMULATE3 values. The comparison of the results illustrates that the QTH model in SIMULATE5 captures the effect of a skewed power and void profile on pin power peaking for the edge pins in the WW side. As expected, this is particularly important for bundles in cells with deep control blades similar to the failed fuel assemblies that were controlled with deep control blade at the time of the failure. These differences jumped to about 15-17% once the channel bow effect was accounted for in the SIMULATE5 calculations for the cells with the largest gap introduced by the channel bow. Although the channel bow is not a known quantity during the core design phase, the ability to perform sensitivity analyses will nevertheless be very valuable in determining the uncertainty in CPR or peak KW/FT with respect to channel bow uncertainties.

The advanced neutronic and thermal hydraulic physics in CASMO5/SIMULATE5 combined with capabilities to model channel bow provide the ability to model many details within the core. The analyses documented in this paper illustrate the CASMO5/SIMULATE5 ability to capture detailed physics and models that can have a significant impact on pin power peaking that is currently ignored by many, due to the lack of capabilities.

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