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EVALUATION OF RODDED BWR ASSEMBLY PIN POWERS WITH SIMULATE5

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ABSTRACT

In the development of Studsvik's nodal code SIMULATE5, special attention has been given to the accurate description of pin powers. The code solves the multi-group diffusion or simplified P3 equations with high spatial resolution. A short description is given of the handling of material heterogeneities in the axial and radial directions – the axial re-homogenization and the radial submesh model, respectively. Furthermore, two models which are of special importance in the presence of control rods, and hence on the pellet clad interaction (PCI) phenomenon, are described; the quarter-assembly thermal-hydraulic treatment and the depletion of absorber material.

A numerical example for a real core shows that while the impact of the fine grained description is negligible on global parameters such as keff, the effect on pin powers may be substantial. For a deeply inserted and highly depleted control rod, the difference in pin powers caused by neglecting the advanced models of SIMULATE5, may be as high as 15 %.

Key Words: SIMULATE5, Pin Power Reconstruction, Control Rod Depletion, PCI

1. INTRODUCTION

The ability to compute pin powers correctly has bearing on a number of primary quantities in reactor core calculations including linear heat generation rate, dry out, fuel temperature, and pellet clad interaction (PCI). In the development of Studsvik's nodal code SIMULATE5 [1,2], the treatment of pin powers has the highest priority, and a set of model improvements have been aimed at this goal.

The heterogeneous pin powers in SIMULATE5 are calculated by modulating multi-group pin powers from the submesh solver with pin form factors from single-assembly CASMO5 [3] lattice calculations. The multi-group pin power model captures instantaneous spectral effects, and the actinide tracking, on the assembly submesh, describes exposure-induced pin power variations. Various advanced neutronic and thermal hydraulic modeling features of SIMULATE5 have direct consequence on assembly pin powers. Specific to BWRs, the capability

of predicting quarter-assembly void distribution and tracking the absorber depletion of a control rod with feedback to cross-sections and pin powers are examples of the advanced features.

The first part of this paper discusses the SIMULATE5 models and features that have significant impact on pin powers. The second part numerically demonstrates the importance of some of the models on various core parameters of interest for a test case drawn from an operating BWR core.

2. MODELS WITH IMPACT ON PIN POWERS

2.1. Multi-group Diffusion or SP3 Theory

SIMULATE5 is based on multi-group diffusion theory or simplified P3 (SP3) theory. Any number of energy groups is allowed as long as it is compatible with the cross sections generated by CASMO5. The number of groups and the transport correction of SP3 have implications for fuel pins at UO2/MOX assembly interfaces where spectral interaction effects are important.

2.2. The Tri-Step Approach

A conventional node of approximate size 15×15×15 cm^3 contains a number of material heterogeneities in both the radial and the axial directions. Traditional core simulators treat the conventional node as materially homogeneous. To overcome this shortcoming, SIMULATE5 has adopted a tri-step approach.

2.2.1. Step-1: Axial heterogeneities:

The axial heterogeneities are treated by individual analysis of each assembly where the bundle has been divided into materially homogeneous subnodes. The boundary condition to this calculation is the radial leakage, which is obtained from step three below, from surrounding assemblies.

2.2.2. Step-2: Radial heterogeneities:

The core is divided into (typically) 25 axial planes. Each assembly in a plane is divided into N×N submeshes. The diffusion equation (or SP3 equation) is solved for the detailed axial layer. The boundary condition to this model is the axial leakage into each plane which is also obtained in step three below.

2.2.3. Step-3: 3D global solution:

The 3D diffusion equation is solved for the conventional 15×15×15 cm^3 mesh by using the analytic nodal method (ANM). Note, that ANM is needed to stitch the axial and radial homogenization models together.

2.3. Axial Homogenization

Inside a ‘conventional’ node, material discontinuities may appear because of 1) enrichment and burnable absorber zoning, 2) part length fuel rods, 3) spacer grids, 4) control rods including handles and different absorber zones, and 5) assemblies of different heights.

The purpose of the axial homogenization model is to compute, per node, averaged cross sections and axial discontinuity factors that faithfully reproduce the correct heterogeneous nature of the assembly and to compute the detailed axial flux and power profile.

Each assembly is axially divided into ‘subnodes’ such that each subnode is materially homogeneous. The subnode layout may differ from one assembly design to another. Also, as control rods move, the axial mesh moves along.

Burnup and nuclide data are stored subnode-wise. Thermal margins are evaluated in this geometry. Hence, the uncertainty of the computation of burnup or thermal margin in a conventional node with discontinuous material properties is avoided.

The axial homogenization module works as follows: The 1D multi-group diffusion equation is solved, one assembly at a time, in the subnode geometry. The radial leakage from neighboring bundles, obtained from the 3D solution (step 3), is converted into an equivalent absorption. The obtained detailed 1D flux is employed to evaluate flux weighting factors needed when computing homogenized cross sections for the ‘conventional’ nodes. Axial discontinuity factors are found. The 1D solution provides a fine grained picture of the flux down to the 1 cm level. Local effects at spacers, control rod tips, etc., can therefore be described in detail.

2.4. Radial Submesh Model

In the radial direction, an assembly is divided into N×N ‘submeshes’ (typically N=5), where the rectangular submeshes follow pin cell boundaries. For BWRs, the outermost layer of submeshes is made up of the water gap region. For PWRs, the outer layer is chosen to be one pin cell layer thick in order to capture intra-assembly mismatch effects (build-up of plutonium etc.). All reflector regions outside the active core are treated in an analogous manner. PWR baffles are represented explicitly.

Submesh interfaces of adjacent assemblies need not match geometrically. Non-matching submesh interfaces appear in BWR cores with mixed fuel assembly designs (e.g. 9x9 vs. 10x10 layouts).

Since BWR water gaps are treated explicitly, the traditional problem of gap-width mismatch effects is solved automatically.

Each submesh has its own cross section and discontinuity factor set as generated by CASMO5. In addition, the variation (as compared to CASMO5) of burnup, isotope composition, fuel temperature, xenon, and coolant density inside the assembly are accounted for. The burnup and the contents of U^{235}, U^{238}, Pu^{239}, Pu^{240}, and Pu^{241} are tracked per submesh. Therefore, the interior material distribution of an assembly is well represented even during such strong-tilted events as operation with control rods.

Although a submesh, consisting of a number of pin cells or of a section of the water gap including any control rod, is not materially uniform, it is considerably less heterogeneous than the full assembly itself. The submesh cross sections and discontinuity factors are therefore less dependent on the CASMO5 boundary conditions (the zero net current assumption) than the full assembly counterparts.

The 2D diffusion equation (or, alternatively, the SP3 equation) is solved, one axial plane at a time, using the submesh geometry. The axial leakage, known from the 3D solution, is converted into an equivalent absorption.

The neutron migration problem is solved by assuming the flux in each group and subnode as

$$\phi(x,y) \quad = \quad \sum_{i=1}^{4} K_i v_i(x,y) \quad + \quad c_0 \quad + \quad \sum_{l=1}^{2} \left(c_{xl} P_l(x) + c_{yl} P_l(y) \right) \qquad (1)$$

where P_l is the Legendre polynomial and

$$v_1 = e^{-\kappa_x x} \quad , \quad v_2 = e^{+\kappa_x x} \quad , \quad v_3 = e^{-\kappa_y y} \quad , \quad v_4 = e^{+\kappa_y y} \qquad (2)$$

The unknown expansion coefficients, K_i, are found from four boundary conditions (submesh average side fluxes). The c_i coefficients are determined by the fission and scattering source expansions.

Once the submesh fluxes are known, re-homogenized cross sections and discontinuity factors for the conventional node are computed. Hence, nodewise nuclear parameters are now calculated with realistic flux and material distributions, thus overcoming the problem created by CASMO5's simplified boundary conditions (zero incoming net currents). Via Eq. (1), the 2D solver provides a detailed homogeneous flux in the x/y directions of each submesh. From the 1D and 3D solvers the homogeneous axial flux shape is known for each pin and subnode. Finally, CASMO5 form functions are superimposed subnode-wise on the homogeneous flux to produce pin powers. Pin burnups are found by time integration of pin powers.

2.5. Quarter-assembly thermal-hydraulic model

Conventionally, core simulators assume that the void distribution inside an assembly is radially flat. For BWRs this is sometimes a poor assumption. At deeply inserted control rods the void across the assembly may vary from 0 to 35 %.

SIMULATE5 offers a thermal-hydraulic evaluation of each quarter-bundle of a BWR assembly (QTH model) as shown in Fig. 1 [2]. Cross-flow is allowed between the assembly quadrants.

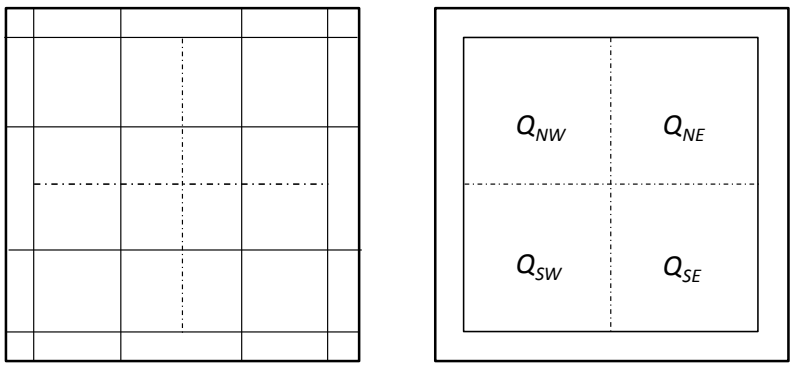

Figure 1. SIMULATE5 submesh and quarter-assembly model

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 quadrant of an assembly is readily available from the radial submesh calculation. The cross flow is obtained by solving the lateral momentum equation.

The results from TH evaluation are fed back to the submesh neutronic calculations through a coolant density distribution. A complication is that normally the four TH quadrants do not geometrically agree with the radial submeshes, as seen in Fig. 1. The density in each submesh is inferred from an interpolation scheme.

The result 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 most 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 for an accurate prediction of the pin power peaking. 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 distributions as well.

SIMULATE5's quarter-assembly TH model has been tested against recent experimental data and has been shown to provide improvements compared to conventional flat void distribution models [4]. In addition, evaluations of pin powers with SIMULATE5 for an operating plant data with failed fuel pellets indirectly confirm that the rodded nodes are more realistically subject to a skewed void/power profile [5].

2.6. Control Rod Depletion

SIMULATE5's control rod depletion model keeps track of active absorber material (whether B^{10}, Hf or any other material) for each wing of a BWR control rod and each pin of a PWR control rod.

The control rod may be heterogeneous in the axial direction with different material zones. Each zone, as well as the control rod tip and handle for BWRs, is represented explicitly by axially dividing the control rod into 'Contol Rod (CR) nodes', whose maximum size is controlled by user input. The CR computational nodalization is independent of the fuel assembly axial nodalization. In addition, the node heights do not need to be uniform. The control rod absorber material and fluence are tracked for each CR nodes. Since the neutron flux is significant in the first 10-20 cm above and below the active core, the completely withdrawn control rod, or the portion of the control rod situated in the top and bottom reflector node, is still subject to depletion.

The CR depletion model relies on the lumped isotope model derived by Z. Weiss [6]. Nuclide *i* is built up through conversion of nuclide *j* and it disappears through neutron absorption as

$$\frac{dN_i}{dt} = -\sum_{j=1}^{I}\left(\delta_{ij} - y_{ij}\right)N_j \sum_{g=1}^{G}\sigma_{ag}^{j}\phi_g^{CR} \qquad i = 1,\ldots,I \tag{3}$$

where δ_{ij} is Kronecker's delta, y_{ij} is the yield of the i-th isotope by the destruction of one nucleus of isotope j, and ϕ_g^{CR} is the average flux in the regions where the absorbing material is located. In the lumped isotope model, individual nuclides i=1,…, I are replaced by an effective isotope with number density

$$N_{eff} = \sum_{i=1}^{I} w_i N_i \tag{4}$$

where the w_i are weights are obtained by solving

$$\sum_{i=1}^{I} \left(\delta_{ij} - y_{ij}\right) w_i = 1 \qquad j = 1,\ldots,I \tag{5}$$

For a linear depletion chain such as that of Hafnium, $y_{i,i-1}$ equals unity and y_{ij} is zero elsewhere. Solving Eq. (5) gives

$$w_i = I + 1 - i \qquad i = 1,...,I \qquad \text{(Linear chain)} \tag{6}$$

The effective isotope is subject to the equation

$$\frac{dN_{eff}}{dt} = -N_{eff} \sum_{g=1}^{G} \sigma_{ag}^{eff} \phi_g^{CR} \tag{7}$$

where the effective microscopic cross section is given by

$$\sigma_{ag}^{eff} = \frac{1}{N_{eff}} \sum_{i=1}^{I} \sigma_{ag}^{i} N_i \tag{8}$$

The lumped isotope has the property of preserving the absorption reaction rates. The depletion of any control rod, whatever its material complexity, can be described by the lumped nuclide, governed by Eq. (7).

The simulator does not explicitly compute N_{eff} but tracks a related quantity β as a function of time

$$\beta(t) = 1 - \frac{N_{eff}(t)}{N_{eff}(0)} \tag{9}$$

The control rod depletion quantity β has the following convenient property

$$0 \leq \beta < 1 \tag{10}$$

where β=0 corresponds to a fresh control rod. Highly depleted control rod tips may reach values up to β=0.8. A typical criterion for maximum allowed burnup is that no rod has an average depletion in the excess of 0.10.

Solving Eq. (7) by integrating over time Δt and employing the definition of β yields

$$\beta_t = 1 - \left(1-\beta_{t-1}\right)\cdot e^{-R_a \Delta t} \quad (11)$$

where the absorption reaction rate R_a is computed using effective absorption cross section and control rod flux where the active material is located.

The effect of the depletion of the active absorber is accounted for via feedback to the cross sections and the pin power shape functions. The conventional cross section functionalization is enlarged to include control rod depletion

$$\Sigma_x(E,\beta,\rho,...) = \Sigma_x^{base}(E,\rho) + \Delta\Sigma_x^{CRD}(E,\rho,\beta)+... \quad (12)$$

where the delta control rod cross-sections, as well as pin form factors, include dependency on control rod depletion fraction, β, for each depletable rod type.

3. NUMERICAL TESTING

A BWR reactor operating in Scandinavia has been used for investigating the impact on fuel pin powers of some of the SIMULATE5 models. A BWR of ABB/Westinghouse design core contains 500 fuel bundles. The core has been depleted from Cycle 1 to Cycle 16 in four different ways, all employing a four-group model:

- The 'Full' option model, which is used as a reference, employs the quarter-assembly TH (QTH) model and the control rod depletion (CRDEP) and radial submesh (SMX) models.
- The 'CRDEP+SMX' model which employs the control rod depletion and radial submesh models. In this model, the QTH model is turned off.
- The 'SMX' model which employs only the submesh model.
- The 'Conventional' model where all three of SIMULATE5's advanced models are turned off. This calculation option is the conventional model employed by most nodal codes.

Note that SIMULATE5's two other advanced features concerning SP3 model and axial homogenization models have been excluded from the numerical testing. As the core contains only UO2 fuel, solving either the diffusion equation or the SP3 equation has no practical consequence. The axial homogenization model is excluded for a different reason. Although most conventional nodal codes do not treat axial heterogeneities as rigorous as SIMULATE5, they employ *ad-hoc* models for control rod cusping and grid effects. A SIMULATE5 model without the axial homogenization would not be representative of a 'conventional' model and therefore not investigated.

In Cycle 16, there is a highly depleted control rod which is deeply inserted into the core throughout most of the cycle. One of the fuel assemblies around this control rod, which is at the same time adjacent to a LPRM/TIP detector, has been examined in detail. The fuel assembly is a

twice burned SVEA-64 design with an average bundle exposure of 20 GWd/MT at beginning-of-cycle (BOC). Fig. 2 presents the assembly quadrant relative powers and void fractions as predicted by the QTH void model. The fuel assembly has a control rod 80% inserted on the north-east (NE) quadrant. In such a case, the power is highly peaked through the opposite quadrant (SW) resulting large void mismatch between quadrants. The peak pin power occurs in axial node # 22, just above the tip of the control rod.

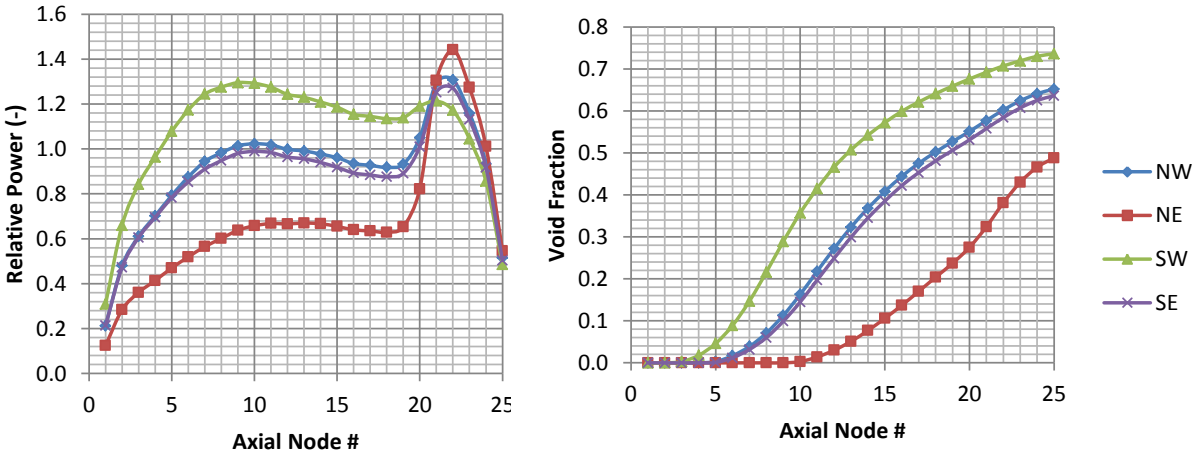

Figure 2. Quadrant Assembly Powers and Void Fractions.

Fig. 3 shows the control rod depletion fraction vs. rod elevation. The control rod design includes both B4C absorber and Hafnium absorber (the top part only). The tip and handle of the control rod, which is mostly stainless steel, are modeled explicitly. Other than the bottom elevations of the rod, which is mostly outside of the core, about 30% of the absorber material is depleted. It should be noted that, the reduction in rod worth due to depletion is much smaller.

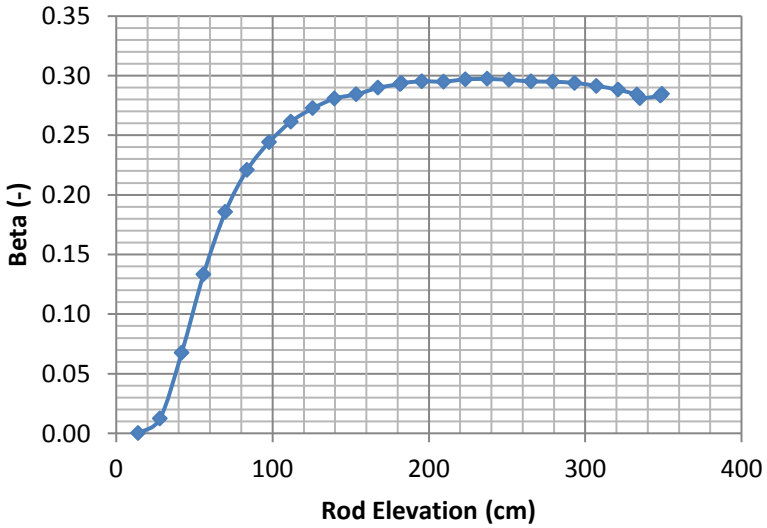

Figure 3. Control rod depletion fractions vs. elevation.

Table I summarizes the cycle eigenvalue and gamma TIP statistics with four different models described above:

Table I. Summary of Cycle Eigenvalue and TIP comparisons

	k-eff		RMS Radial		RMS Axial		RMS Nodal	
Model	**Ave**	**StDev**	**Ave**	**StDev**	**Ave**	**StDev**	**Ave**	**StDev**
QTH+CRDEP+SMX (Full)	1.00214	0.00065	1.76	0.12	2.36	0.35	3.49	0.25
CRDEP+SMX	1.00171	0.00064	1.59	0.15	2.26	0.33	3.31	0.29
SMX	1.00156	0.00064	1.62	0.15	2.24	0.32	3.34	0.27
None (Conventional)	1.00120	0.00058	1.61	0.05	2.28	0.31	3.33	0.21

There is no significant difference on core *global* parameter predictions with any of the models. This is due to the fact that the model enhancements of SIMULATE5 affect mainly the distributions *within* an assembly. Errors inside a bundle tend to average out when looking at global parameters. To see effects of the model enhancements, one has to look at the pin power distribution in channels with a substantial flux gradient.

Fig. 4 shows the average pin power, which can also be interpreted as node power, of the assembly with the deeply inserted control rod. The plot includes the reference results computed with the 'Full' model as well as the effect of each individual model, which are computed by taking the difference in two related models and plotted as the % difference. For example, the delta term for the CRDEP effect is computed by taking the difference between the 'SMX' only and 'CRDEP+SMX' models and represents how much the node/pin powers would change if the model is not employed in the calculation. Finally, the plot includes the difference between the 'Full' and 'Conventional' models in which the effect is essentially the sum of each three individual components.

The differences in average pin powers due to each individual model are typically small and in the range of -4% to +4%. The effect of quarter-assembly thermal-hydraulic (QTH) and submesh (SMX) models is more pronounced for nodes with skewed power distribution. The modeling of control rod depletion with the cross-section feedback increases the power in rodded nodes. The combined effect, as shown in the conventional model, is about 5% under prediction for the entire part of the fuel with control rod inserted.

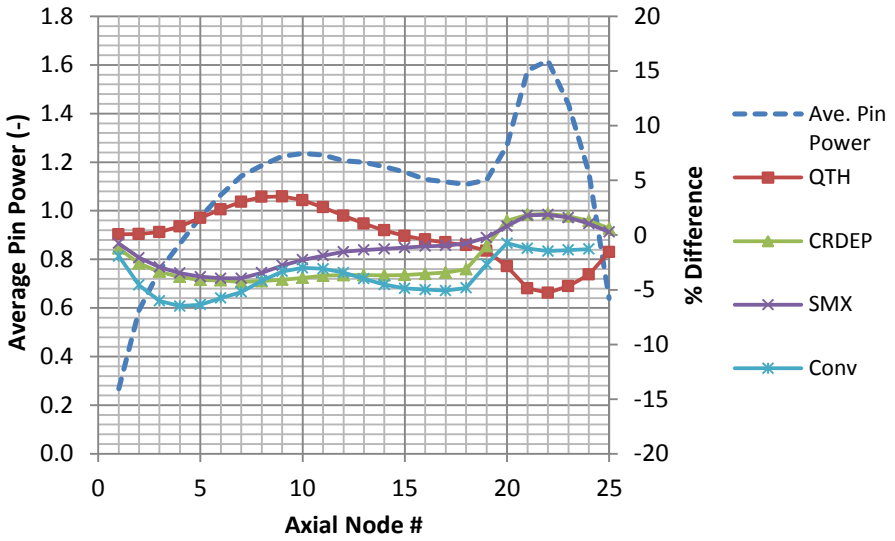

Figure 4. Comparison of average pin/nodal powers

Fig. 5 shows the comparison of gamma detector response at the TIP location adjacent to the fuel assembly of interest. Note that the TIP/LPRM tube is located on the south-west corner of the assembly. The difference between the 'Full' and 'Conventional' model errors is significantly smaller, around 1%, compared to the differences in node average pin powers. This is due to the fact that the detector is surrounded by four assemblies where the remaining three assemblies are unrodded, the difference in average detector signal is less sensitive to the models employed in the solution.

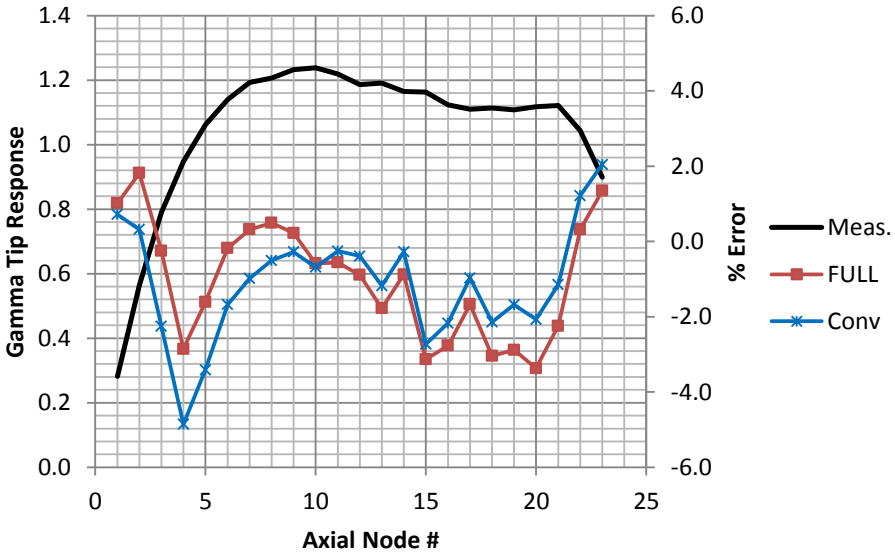

Figure 5. Comparison of gamma TIPs

Fig. 6 is an equivalent of Fig. 4 for the peak pin power in each axial plane. The conventional model under-predicts the maximum peak pin which occurs at axial node #22 (one node above the tip of the control rod) as much as 15%.

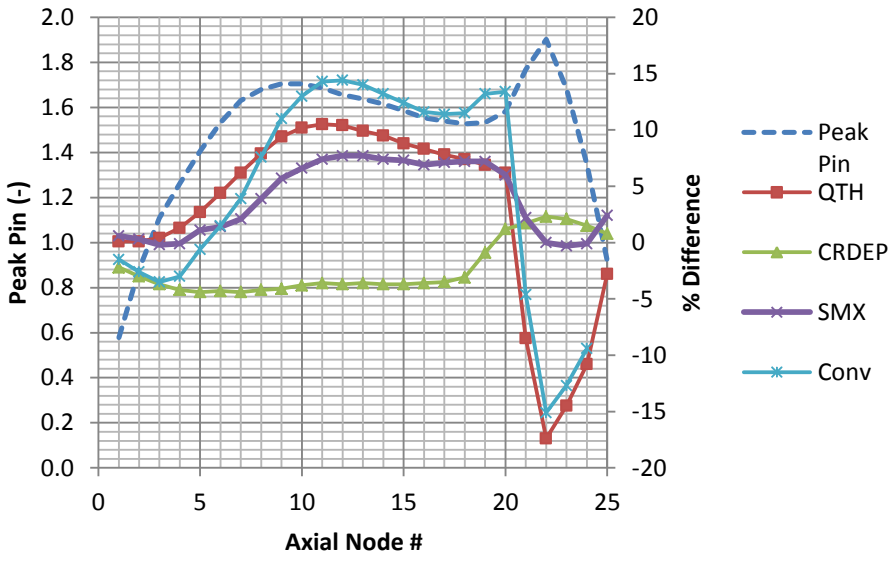

Figure 6. Comparison of peak pin powers

Fig. 7 shows pin-by-pin powers and % difference in pin powers with different models at three axial planes. Recall that the control rod is inserted in the NE quadrant. The lack of a quarter-assembly thermal-hydraulic (QTH) in the solution, as shown in Fig. 7-b, results in lower pin powers in NE quadrant, which is adjacent to the control rod, and higher pin powers in SW quadrant, which is away from the control rod. The effect of control rod depletion on pin powers (Fig. 7-c) is rather uniform across the assembly. The omission of the model yields 3-4% under prediction on lower rodded planes and 1-2% over prediction on planes above the tip of the rod. The SMX model effect is similar to that of the QTH model but with smaller magnitude.

The peak pin in SW quadrant of lower rodded planes moves to NE quadrant above the tip of the rod. The difference between the 'Full' and conventional model is mostly driven by the QTH model. Reduced quadrant power and therefore lower void/higher moderator density with the QTH model at and above the control rod tip result in higher pin peaking.

It should be noted that in assemblies with a skewed power distribution, the radial void distribution inside the quarter sub-channel itself may still be large. For pins adjacent to a control rod blade, the effect of local void would be even larger than indicated by the QTH model of SIMULATE5, since the code employs an average void value for the control rod quadrant, not the detailed pin cell void. Although this is not considered by SIMULATE5, the code nonetheless offers a considerable improvement compared to conventional methods.

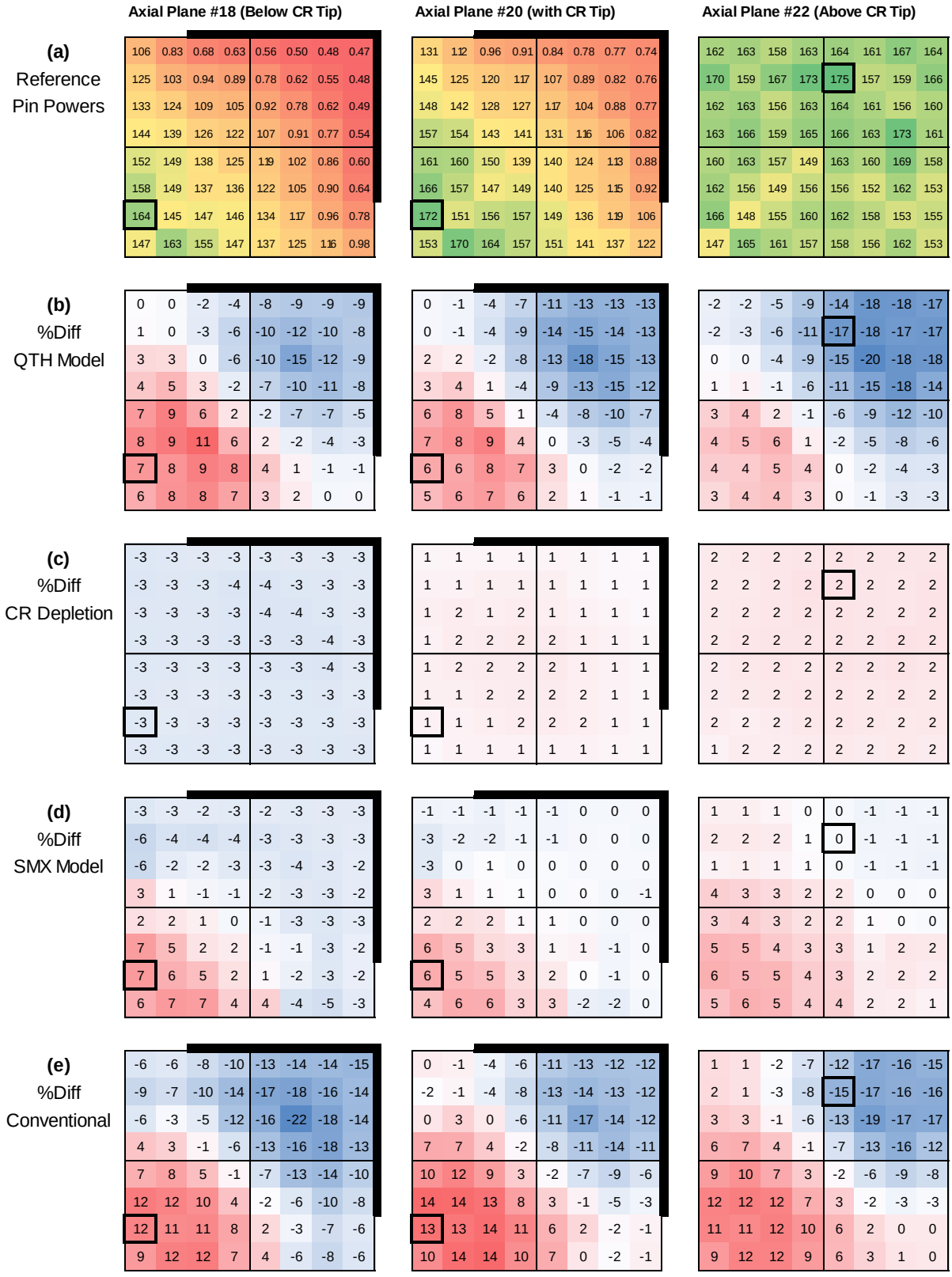

Figure 7. Comparison of pin powers (Axial planes 18, 20 and 22)

4. CONCLUSIONS

Various advanced models of SIMULATE5 that have an impact on assembly pin powers have been examined for a BWR assembly with deeply inserted highly depleted control rod. Although the impact of most of these models is insignificant on core global parameters such as core eigenvalue and TIP comparisons, omitting them may lead significant errors in predicting local pin peakings. For the test case analyzed, it was demonstrated that the quarter-assembly thermal-hydraulic model has the most significant impact on pin power for assemblies with skewed intra assembly power shape. The modeling of control rod depletion with cross section feedback has a direct impact on node powers which is reflected on pin powers. Combining the advanced thermal-hydraulic with advanced neutronic models, SIMULATE5 offers improved accuracy on pin powers for such highly challenging cases.

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