Advances in Nuclear Fuel Management IV (ANFM 2009)
Hilton Head Island, South Carolina, USA, April 12-15, 2009, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2009)

TESTING 3-D NODAL CODES SIMULATE-3/5 FOR REFUELING SHUTDOWN MARGIN PREDICTIONS WITH CASMO-5M

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Keywords: Reactor refueling, shutdown margin, partially loaded core

ABSTRACT

Reactor shutdown refueling is a crucial task for BWR operations. In this paper, based on a realistic BWR core refueling sequence, the SIMULATE-3 and SIMULATE-5 shutdown margin (SDM) predictions are benchmarked against CASMO-5M results. The 2-D core in this exercise is established from the middle plane of a typical 748-bundle BWR core. There are thousands of fuel move steps from the end of previous cycle to the beginning of next cycle, most of which are so-called partially loaded core configurations where empty fuel locations are filled with water. During this process, eigenvalue predictions from CASMO-5M and SIMULATE-3/5 are compared for the all-rod-in (ARI) case and the ARI except the maximum-worth rod (ARI-M) case. Based on more advanced neutronic models, SIMULATE-5 shows sizable improvements in agreeing with the CASMO-5M reference solution over the SIMULATE-3 results for partially loaded cores.

1. INTRODUCTION

Reactor shutdown refueling is a crucial task for BWR operations. Typically there are thousands of fuel move steps between the end of previous cycle and the beginning of next cycle. The core shutdown margin (SDM) requirement needs to be satisfied during every step of the fuel shuffling and core reload process, which necessitates an accurate core eigenvalue prediction for partially loaded cores under cold conditions. In the production analysis, the advanced 3-D nodal code, SIMULATE, is utilized for this purpose. Note that the shutdown margin evaluation assumes all control blades inserted except the maximum-worth one (ARI-M).

In this paper, based on a realistic BWR core refueling sequence, the SIMULATE version 3 and version 5 SDM predictions are benchmarked against reference CASMO-5M results. Since CASMO-5M[1] is a 2-D lattice physics code capable of modeling M×N fuel segments in rectangular geometry, the benchmark exercise is proposed as a 2-D core problem established from the middle-plane of a typical 3-D 748-bundle BWR core. It is recognized that 2-D BWR core calculations are not realistic. Therefore, the calculations reported here serve for benchmark purposes only.

During the process of fuel move steps, eigenvalue predictions from CASMO-5M and SIMULATE are compared against each other for the all-rod-in (ARI) condition and the ARI except the maximum-worth rod (ARI-M) condition. The SIMULATE nodal cross section library is created from single-assembly CASMO-5M lattice calculations. SIMULATE-3[2] is based on a well-known two-group nodal model, whereas SIMULATE-5[3,4] adopts a generalized multi-group analytic nodal model.[*]

For this 2-D benchmark problem, there are several assumptions when transferring from the real plant shutdown refueling calculations:

1) All fuel assemblies have a constant nominal hot-full-power (HFP) depletion history, i.e., fuel temperature at 900 K, water temperature at 561.5 K, coolant at 40% void and no control rod inserted.

2) For simplicity, the actual fuel assembly exposure values in the 2-D core are rounded to the nearest CASMO default burnup points (0.1, 0.5, 1.5, 2.5, 5, 7.5, 10, and every 2.5 MWd/kg afterwards). For example, the fuel exposure value of 10.1 MWd/kg is rounded to 10.0 MWd/kg.

3) All cases are assumed xenon free. CASMO-5M explicitly zeroes xenon number densities in all fuel regions. In SIMULATE, xenon is set to zero by using the proper fission product option.

4) CASMO-5M explicitly models empty fuel locations filled with cold water, whereas, in SIMULATE, the water nodal cross section data comes from CASMO reflector calculation.

5) In reality, control blade guides are used to structurally support the control blade when two diagonal bundles are removed from the core. In this paper, no control blade guides are considered.

6) The BWR core is at isothermal room temperature of 20°C (so-called cold condition) throughout the refueling.

The benchmark calculation is performed on two spatial scales: 10×10 mini core and full core. The 10×10 mini core is taken from the full core as a simplified problem. Choosing such a small mini core significantly reduces the computational demand for CASMO-5M, which, in turn, makes it possible to perform a scoping calculation for the entire refueling sequence. In contrast, only a few selected fuel move steps are examined by CASMO-5M for the full core problem.

2. CASMO-5M MODEL SETUP

Based on the method of characteristics, CASMO-5M is a multi-group 2-D transport theory code capable of M×N fuel segments in rectangular geometry. It is an extension of the single-assembly lattice physics code, CASMO-5. The nuclear data for

[*] SIMULATE-5 is the commercial version of the SIMULATE-4 development version.

CASMO-5M are collected in a library containing microscopic cross sections in 586 energy groups. The current 586-group neutron data library is based on ENDF/B-VII.0 data files[5].

For each fuel move step, two CASMO-5M inputs are created, i.e., one for ARI and one for ARI-M. In general, the 2-D core, either a 10×10 mini core or a full core, contains several types of segments: irradiated fuel from last cycle, fresh fuel and water holes. For fuel segments, a restart file is read from the single assembly CASMO-5 depletion with the assumed depletion history, and the depleted fuel number densities are taken at the specified exposure point. For water holes, CASMO-5M creates appropriate composition of liquid water in that location, where the temperature is set in the input. The cruciform control blades are also modeled explicitly.

The CASMO-5M calculation options include: transport-corrected P0 scattering, 19-group 2-D transport calculation, and a uniform 2-D quadrature of 64 azimuthal angles, 3 polar angles, and 0.05 cm ray spacing. The 10×10 mini core problem has about half million flat source regions, and the full core problem has about five million flat source regions. Sensitivity calculations, e.g., P3 scattering and more 2-D groups, show that these options provide converged solutions.

3. SIMULATE-3/5 MODEL REVIEW

SIMULATE-3 and SIMULATE-5 are 3-D steady-state codes based on few-group nodal methods. In this model, the 3-D reactor core is divided into several large-size regions called nodes. For example, in a BWR core there are about 24 axial fuel nodes and each fuel bundle represents a radial node. For each node, the cross section data, provided by single-assembly CASMO-5 calculations, are functionalized versus various operating condition variables and depletion histories. In this paper, the CASMO-5 single-assembly calculations are performed for each type of fuel segments in the core. Cold libraries are generated to cover the refueling shutdown scenario.

By performing 2-D refueling shutdown margin benchmark against the CASMO-5M reference solution, the SIMULATE-3/5 models under testing would include:

- Single-assembly cross section generation
- Reflector data used for both water holes and core reflectors
- Two-group nodal model for SIMULATE-3, and a generalized multi-group analytic nodal model for SIMULATE-5
- Quadratic approximation of transverse leakage
- Assembly homogenization with the usage of discontinuity factors
- Re-homogenization of cross sections
- Cross section functionlization

Note that the SDM problem is a cold problem. Hence, no thermal hydraulic models are involved.

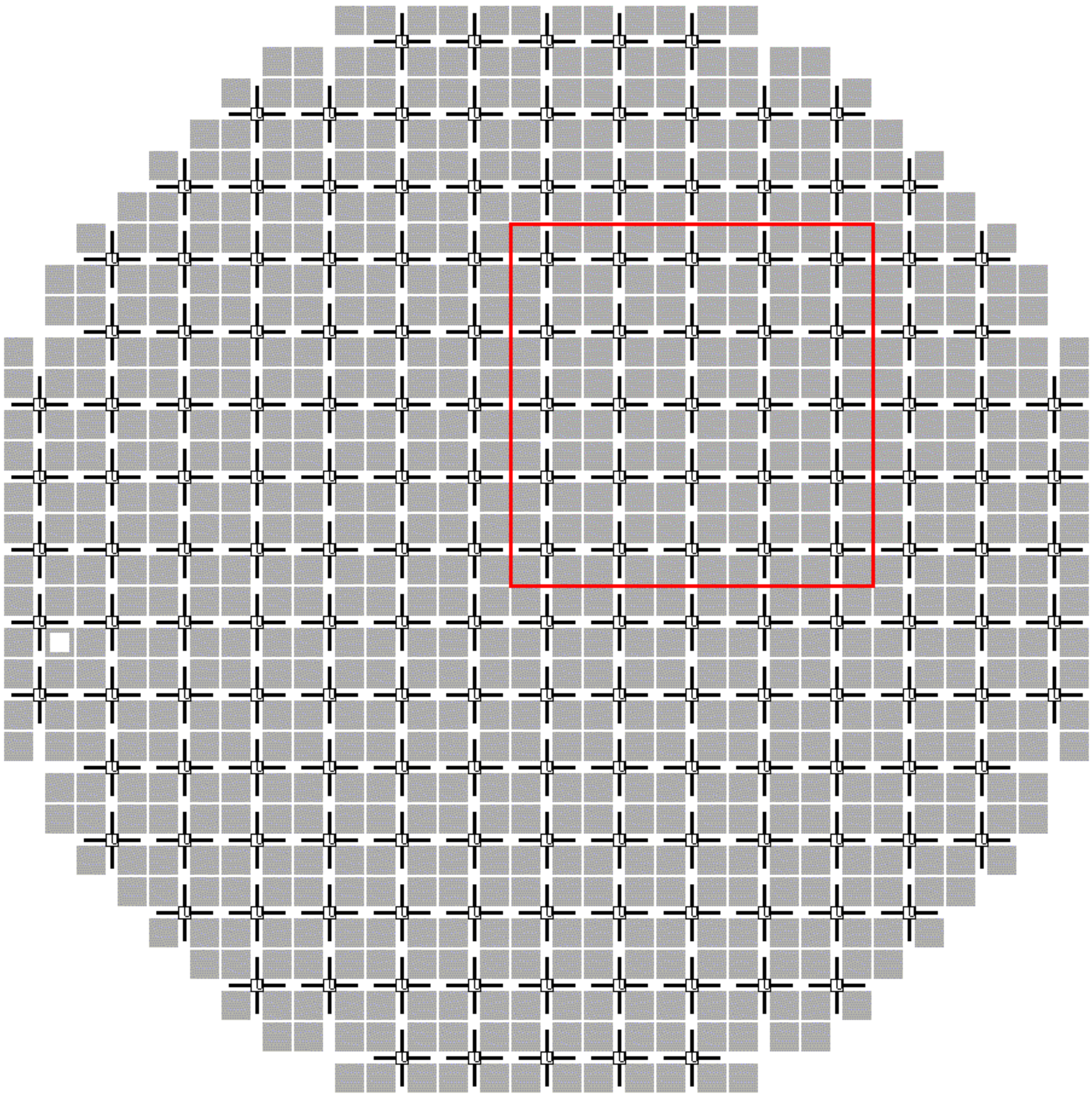

Fig. 1 Illustration of 2-D BWR core.

4. 10×10 MINI CORE

As shown in Fig. 1, the 10×10 mini core as indicated in red box is taken out from top-right quadrant of the 2-D BWR core. There are only 126 fuel move steps in the 10×10 mini core area during the actual refueling shutdown fuel move schedule. Fig. 2 shows the number of fuel of different types during the refueling process. Immediately following the start of the refueling, 38 burnt fuel bundles are directly taken out of the core, leaving empty locations filled with water. Some used fuel bundles are then re-inserted, and fresh fuel bundles are gradually introduced into the core until the next BOC core configuration is achieved. It is of interest to note that in this refueling schedule, about 10% of the original fuel bundles do not move.

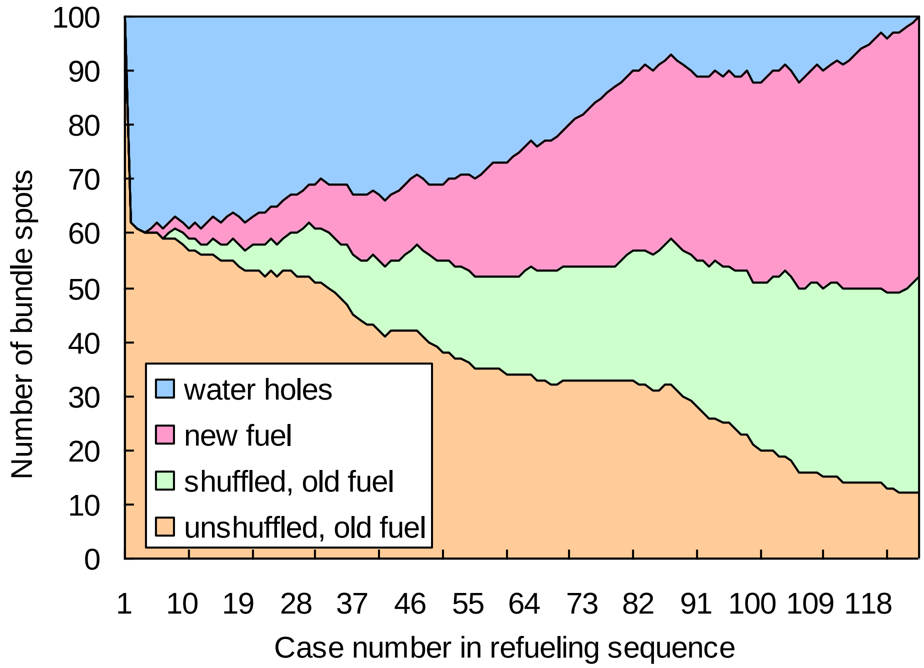

Fig. 2 Fuel bundle types during refueling in the 10×10 mini core.

The control rod array is 5×5 in the mini core. Since mirror boundary conditions are assumed, control rods closer to the boundary have much higher worth than the central ones. The SDM evaluation in this case is assumed as ARI-C (all rods inserted except the center one). Obviously, in reality, the maximum-worth rod in the core will change its location depending on the actual core configuration. The assumed simplification is only for this particular 2-D 10×10 mini core with mirror boundary conditions.

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Fig. 3 Control rod labeling for the 10×10 mini core.

CASMO-5M reference eigenvalue results are shown in Fig. 4 for both ARI and ARI-C cases. The initial sharp eigenvalue decrease is due to the removal of used fuel bundles. Before case 60, the two curves almost fall on top of each other since the fuel assemblies in the center of mini core are discharged leaving empty water holes. Once the fuel bundles are introduced around the center control blade, the two curves become readily distinguishable where the difference indicates the reactivity worth of the center control rod. One can also observe that the eigenvalue is constant over several small intervals. During the cold shutdown refueling process, the core is loosely coupled. The eigenvalue is dominated by a few active spots in the core. Unless the current most active spot is perturbed or a new active spot is created by introducing a reactive bundle, the core eigenvalue will not have appreciable changes. This characteristic will be more evident when looking at 2-D full core results.

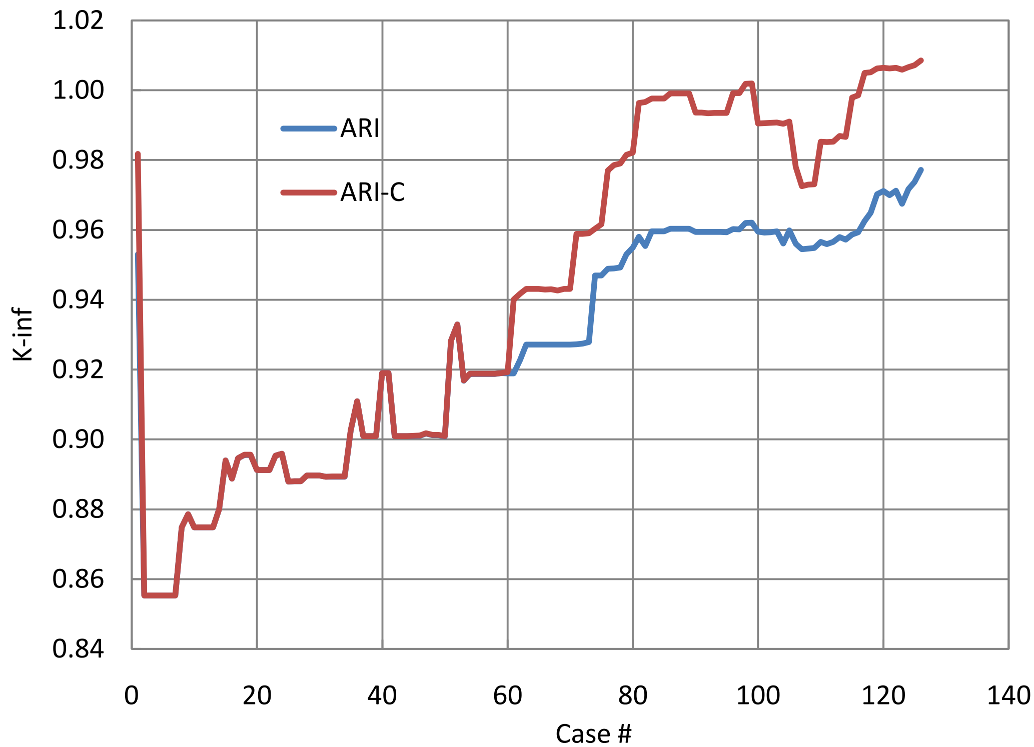

Fig. 4 CASMO-5M reference results for the 10×10 mini core.

Next, Figs. 5 and 6 show SIMULATE-3/5 vs. CASMO-5M benchmark results for the ARI and ARI-C cases respectively. The trends are similar for both cases, i.e., large errors occur in the middle of the refueling. Near the end of previous cycle and beginning of next cycle, there are fairly good agreements on the order of about 200 pcm between SIMULATE-3/5 and CASMO-5M. This is consistent with typical benchmark experiences as these configurations have no or very few water holes. In the middle part of refueling, there are partially loaded core configurations where SIMULATE-3 eigenvalue predictions can be about 800 pcm in error from the reference CASMO-5M results. However, these errors occur in configurations where there is substantial margin. With more advanced neutronic models (analytic nodal method, submesh cross section model, etc.), SIMULATE-5 gives better results even with a similar two-group cross section library. Four-group SIMULATE-5 results are further improved perhaps due to capturing the fast leakage effect across the water holes with more fast energy groups. In summary, SIMULATE-5 yields a much better neutronic solution for the partially loaded cores than SIMULATE-3 when judging by the reference CASMO-5M results. SIMULATE-5, therefore, is expected to enhance the fidelity of the refueling shutdown margin evaluation.

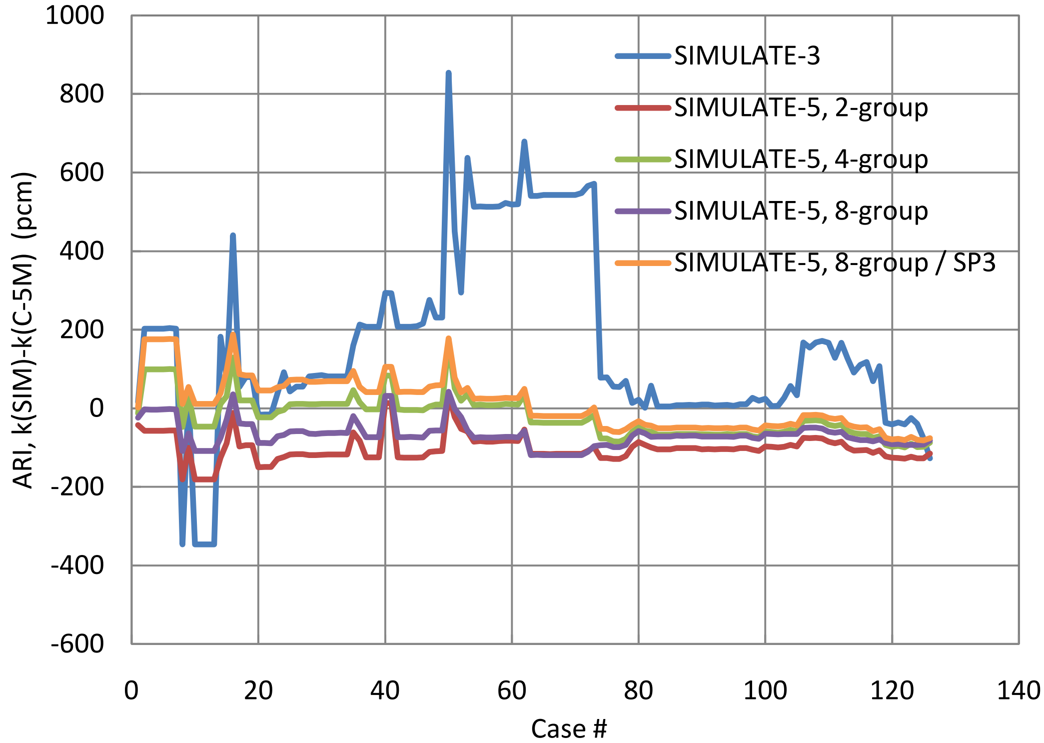

Fig. 5 SIMULATE-3/5 vs. CASMO-5M benchmark result for the ARI case.

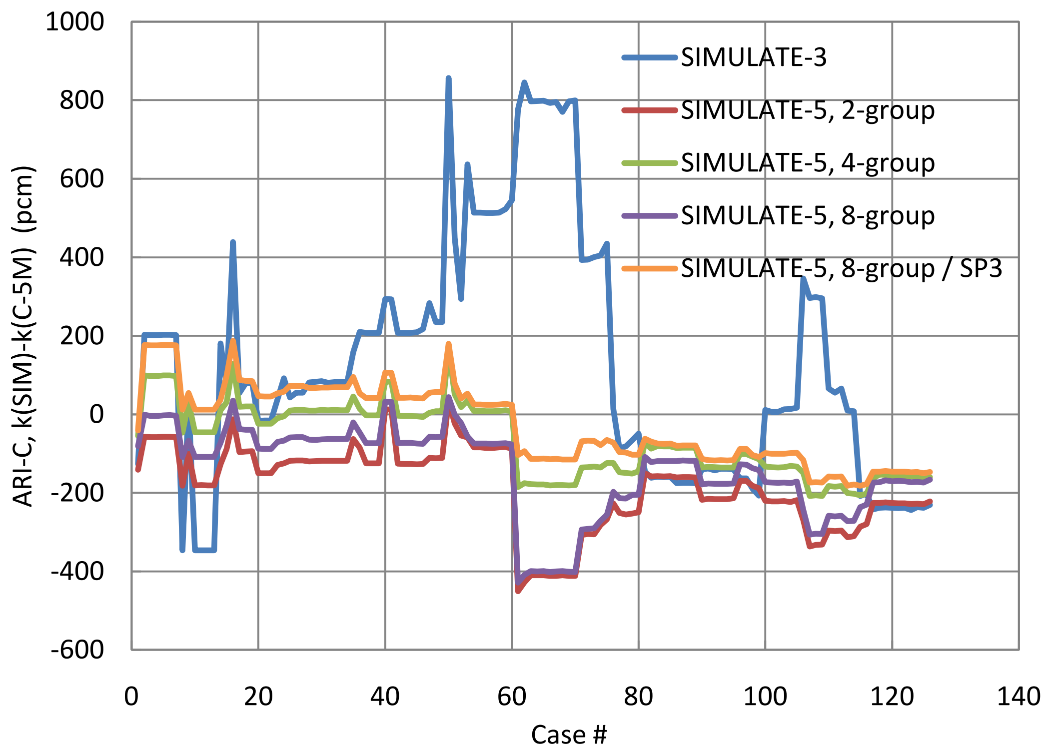

Fig. 6 SIMULATE-3/5 vs. CASMO-5M benchmark result for the ARI-C case.

5. FULL CORE

The 10×10 mini core is a test problem for scoping studies. A 2-D BWR full core is a more interesting case as shown in Fig. 1. However, the 2-D full core problem is much more demanding in terms of computational resources, i.e., CPU time and memory. Even though the BWR core has 30×30 fuel bundles, CASMO-5M needs to model a square area of 32×32 segments to include an additional layer of water reflectors.

SIMULATE-3 is used to perform the shutdown margin (SDM) calculations for the entire full core refueling sequence. In SIMULATE-3 by default, the 3-D two-group QPANDA calculation is performed only for control rods within 0.1% of minimum SDM of the screening 2-D one-group calculation. For the 2-D full core problem in the paper, QPANDA solution is applied for every rod in the core to identify the maximum-worth rod. CASMO-5M, then, calculates the reference solution for the ARI and ARI-M cases.

Fig. 7 shows the 2-D full core SIMULATE-3 results for the entire refueling sequence. Compared to the 10×10 mini core, the characteristic of partially loaded cores is more evident, i.e., the eigenvalue curve consists of a few flat lines connected with rapid changes. As a local effect, the SDM eigenvalue is governed by the most active part of the core.

Fig. 8 shows a typical partially loaded core configuration, where the red circle indicates the maximum-worth rod. Scattered water holes can be seen across the core. In reality, the design of a fast fuel move sequence is a challenging task. The goal is to minimize time while satisfying several constraints including the SDM requirement. There is a Studsvik code, MARLA[6], to perform the automated design and analysis of a BWR fuel shuffle.

Table 1 shows the numerical results. The fuel move step number 1406 corresponds to the 10×10 mini core number 60 where there is about 600 pcm over-estimation in SIMULATE-3 for the ARI-C case (Fig. 6). In contrast, the 2-D full core result only shows about 300 pcm underestimation for the ARI-M case in SIMULATE-3. This suggests that even though the 10×10 mini core area has a challenging partially loaded core configuration, there are still clustered fuel regions in the full core. In this sense, the full core problem appears to be easier than the 10×10 mini core. SIMULATE-5 results are generally better than the SIMULATE-3 results. From the balance point between running time and accuracy, the SIMULATE-5 4-group solution is a preferred option.

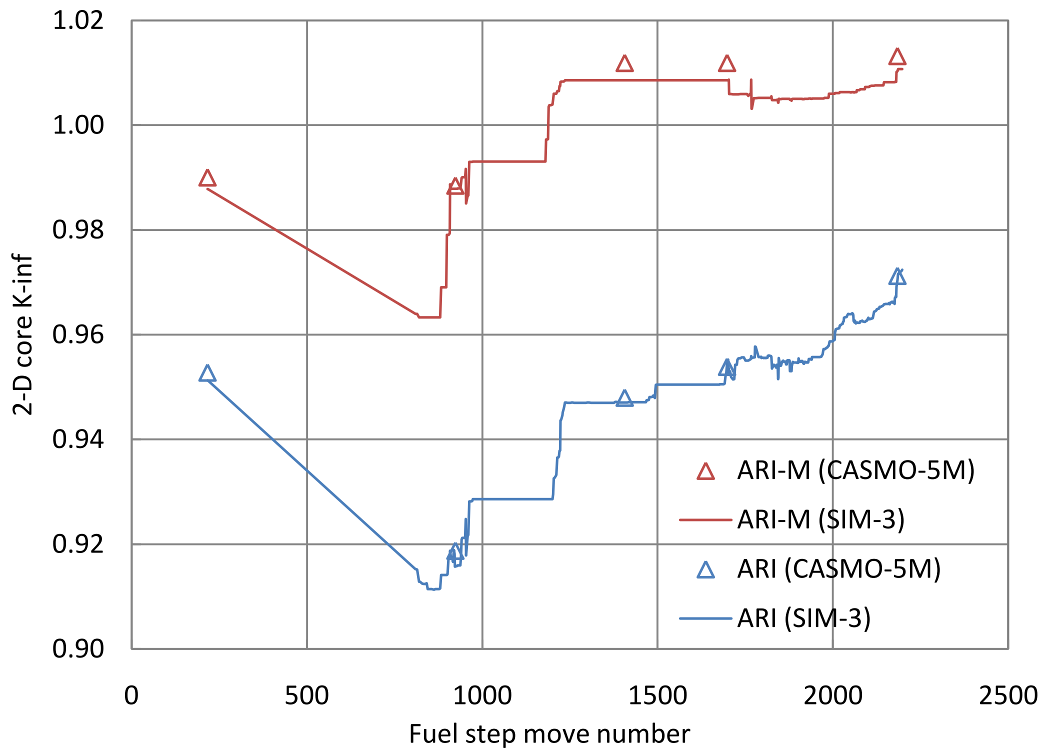

Fig. 7 2-D full core SDM SIMULATE-3 results.

Table 1 SIMULATE-3/5 vs CASMO-5M ARI-M eigenvalue benchmark results.

Fuel step move number	0216	0923	1406	1698	2184
CASMO-5M	0.99009	0.98852	1.01194	1.01194	1.01326
SIM-3	-228	-63	-336	-336	-295
SIM-5, 2-group	-135	-103	-203	-204	-194
SIM-5, 4-group	-48	-2	-129	-129	-133
SIM-5, 8-group	-70	-54	-151	-150	-143
SIM-5, 8-group / SP3	-34	12	-116	-116	-126

∗ All SIMULATE results shown are eigenvalue difference with respect to CASMO-5M values in units of pcm.

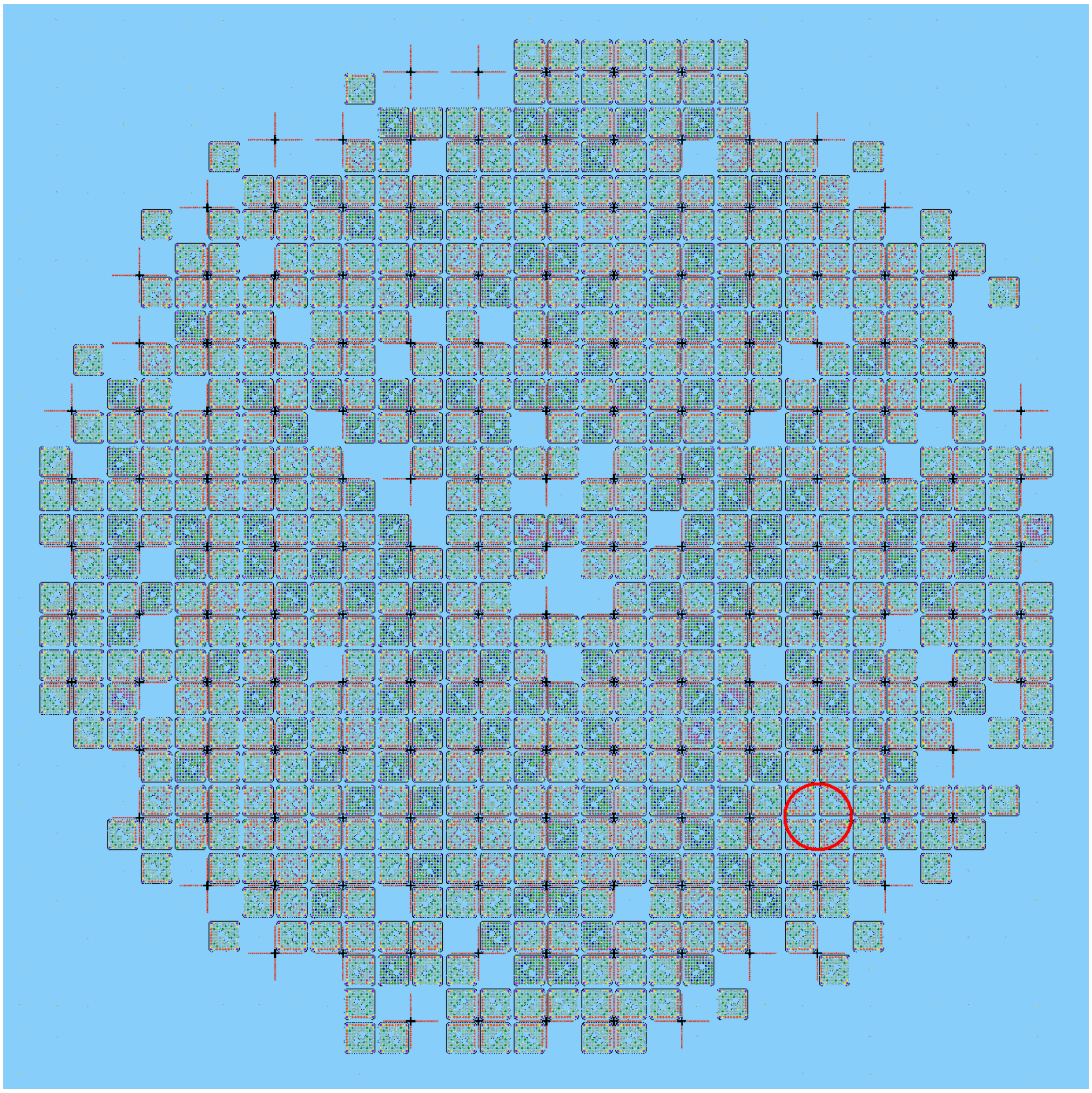

Fig. 8 A typical partially loaded core configuration.

6. CONCLUSIONS

In this paper, the 3-D nodal codes, SIMULATE-3 and SIMULATE-5, are tested for the refueling shutdown margin predictions using the high-order lattice physics code, CASMO-5M. Based on a realistic BWR core refueling sequence, satisfactory SDM eigenvalue agreements can be observed between SIMULATE-3/5 and CASMO-5M for the BWR cores with only few water holes, i.e., near the beginning and the end of the refueling sequence. However, there exists substantial differences, about 800 pcm in eigenvalue, between SIMULATE-3 and CASMO-5M reference solution for the 10×10 mini core ARI-C case in the middle of the refueling. Even though these large errors only occur in configurations with substantial SDM margin, it is obvious that these partially loaded cores pose a serious challenge for SIMULATE-3. Based on more advanced neutronic models, SIMULATE-5 is shown to appreciably improve the eigenvalue predictions for these partially loaded cores. Together with the most-recent Studsvik lattice code, CASMO-5M, SIMULATE-5 is expected to provide a high-fidelity refueling shutdown margin prediction over the entire refueling sequence.

ACKNOWLEDGMENTS

The primary author would like to thank former Studsvik Scandpower employee, Dr. Scott Palmtag, for providing valuable initial guidance in the simulation work, and the colleague, Dr. Tamer Bahadir, for his great help in running SIMULATE-5.

REFERENCES

1. J. RHODES, K. SMITH, D. LEE, "CASMO-5/CASMO-5M, A Fuel Assembly Burnup Program, User's Manual," SSP-07/431 Rev 0, Studsvik Scandpower, Inc. (2007).

2. J. CRONIN, K. SMITH, D. VER PLANCK, "SIMULATE-3 Methodology," Studsvik/SOA-95/18 Rev 0, Studsvik of America, Inc. (1995).

3. T. BAHADIR, S-O. LINDAHL, "Studsvik's Next Generation Nodal Code SIMULATE-5," *Advances in Nuclear Fuel Management IV (ANFM 2009)*, Hilton Head Island, South Carolina (2009).

4. T. BAHADIR, "SIMULATE-4, User's Notes and Manual," SSP-08/454, Studsvik Scandpower, Inc. (2009).

5. M. B. CHADWICK, P. OBLOZINSKY, M. HERMAN et al., "ENDF/B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology," *Nuclear Data Sheets*, **107**, 2931 (2006).

6. D. KNOTT, C. OYARZUN, "MARLA, BWR Shuffle Design and Licensing-Grade SDM Analysis," *Advances in Nuclear Fuel Management IV (ANFM 2009)*, Hilton Head Island, South Carolina (2009).