INTRODUCTION

As part of the Consortium for Advanced Simulation of Light Water Reactors (CASL), the Virtual Environment for Reactor Applications (VERA) is being developed to provide high-fidelity multiphysics simulations of nuclear reactor cores [1, 2]. VERA contains a number of single physics packages that are coupled together. MPACT [3] is the primary deterministic neutron transport solver, CTF [4] provides thermal hydraulics solutions, and BISON [5]—which is built off of the MOOSE framework [6]—is used for fuel performance simulations.

Over the past year, a standalone BISON capability has been developed using a one-way coupling between MPACT/CTF coupling calculations and BISON. This has allowed CASL contributors to gain insight into the fuel performance characteristics while a more tightly coupled methodology between MPACT, CTF, and BISON has been under development [7, 8]. The standalone capability has been used to simulate Watts Bar Unit 1 (WBN1) Cycles 1–3 [9] and to screen for quantities of interest to pellet-clad interaction in Cycles 6–7 [10]. The simulation and screening results are presented here.

CASL recently partnered with Exelon and the University of Illinois at Urbana Champaign (UIUC) to begin simulating some of Exelon’s plants, with particular focus on load-follow operations. In such operations, the power output from the plant will vary based on the demand or anticipated demand at the time. For example, demand is much lower late at night than during the day when people are awake, so it operating the plant at lower power in the evenings could be advantageous. Historically, nuclear power generation has been among the cheapest sources of energy, so most plants in the United States have been operated at full power except for outages and various small scale events. However, in the current economic climate, priorities have changed.

A number of questions arise when load-follow operations are considered, particularly with respect to VERA’s tools and capabilities. Can the coupled neutronics and thermal hydraulics simulations with MPACT, CTF perform well without substantial convergence issues? Can BISON handle the somewhat rapid power changes present with load-follow? Will clad hoop stresses be alarmingly high as a result of these power changes? This work addresses these questions and demonstrates operations to assess feasibility and robustness before Exelon and UIUC proceed with their simulations using VERA.

To demonstrate load-follow capability, two test problems were developed. The first is a single rod that experiences nominal operations during Cycle 1, and then it simulates 18 months of representative load-follow operations in Cycle 2. This single-rod case was used to test the robustness of MPACT, CTF, and BISON on a typical rod. The second problem is a quarter-core model based on WBN1, Cycle 3 [11], with a single month of load-follow operations inserted into the middle of the cycle. This provides better understanding of the stresses to the clad during the numerous power changes.

Sections of this article are adapted from the original, full technical report on this capability [12].

WATTS BAR UNIT 1, CYCLE 3 DESCRIPTION

The Watts Bar Nuclear Plant is a Westinghouse four-loop pressurized water reactor (PWR) operated by the Tennessee Valley Authority (TVA), online since 1996. It began with a 3,411 MWth power rating, but it had a 1.4% power uprate in 2001. It is currently operating in its fourteenth cycle, logging over 6,000 effective full power days (EFPDs) of operation [11].

The unit has 193 Westinghouse 17 × 17 fuel assemblies which are 12 feet tall, with 264 fuel rods and 25 guide/instrumentation tubes. Axially, the VERA models include upper/lower core plate, nozzles, and gaps, with two Inconel and six Zircaloy spacer grids.

Figure 1 shows the core layout in Cycle 3. Each assembly is color-coded based on enrichment. Depictions of fresh assemblies include data on the number of integral fuel burnable absorber (IFBA) and wet annular burnable absorber (WABA) rods, while others contain corresponding locations from previous cycles. The center assembly (H-8) comes directly from Cycle 1, skipping Cycle 2 operations.
Fig. 1. Watts Bar Unit 1 – Cycle 3 core layout, which was used as the basis for the quarter-core test problem.

**REPRESENTATIVE POWER HISTORY**

A nonproprietary core power history was chosen for this work to allow for easier documentation and dissemination of the demonstration. Exelon engineer Christopher Demetriou provided a single month of hour-by-hour power history data corresponding to representative load-follows operations. These data are not based on any particular plant’s operation, but they indicate the power changes Exelon expects during these types of operations. Figure 2 shows Exelon data (hourly, blue) and the condensed representation used in VERA (green). The condensed data represent 101 statepoints to make the calculations more tractable than the hourly data, which would have yielded 744 statepoints.

**RESULTS**

To demonstrate this capability, two test problems were analyzed: (1) a single rod with 18 months of load-follow operations during Cycle 2 and (2) a quarter-core problem based with a single month of load-follow operations data appended after roughly half a cycle of nominal operations. The third cycle was chosen to allow for results with fresh, twice-, and thrice-burned assemblies to be obtained. Depleting half-way through the cycle allows for some of the fresh fuel, particularly in higher power regions, to have some level of fuel-clad contact.

**Single Rod**

Before proceeding with a larger quarter-core case, a single rod case was used to try to expose convergence issues which might be expected with a larger case. It used nominal operations for Cycle 1 to ensure fuel-clad contact before proceeding into the load-follow operations in Cycle 2, which were simply a single month of representative data appended 18 times, amounting to roughly 1,800 statepoints. Despite this large number of power oscillations, MPACT/CTF ran successfully. The output from MPACT/CTF was then used to set up and complete the BISON case, which also finished successfully, giving some confidence in the tools’ ability to handle this many power ramps. For brevity, the more detailed results from this case have been omitted: Reference 12 provides a full set of results.

**Quarter-Core**

With results from the single rod in hand, simulations for the quarter-core case could proceed. The first step was to run MPACT/CTF for Cycle 3 with modified power history to include the single month of load-follow operations in the middle of the cycle. The completed results (in combination with the nominal power history results for Cycles 1 and 2) were used to build the BISON inputs for each rod in the quarter-core case, linking up the multicycle data as appropriate to simulate the full history of the rod. To present the results, four statepoints from the simulation were selected to highlight changes during the cycle:

1. hot zero power (HZP), State 1 (0 GWd/MT)
2. early in hot full power (HFP) operations, State 7 (3.51 GWd/MT, 100% power)
3. start of load-follow operations, State 13 (9.201 GWd/MT, 100% power)
4. low power point in load-follow, State 90 (11.18 GWd/MT, 70% power)

These are shown by the red dashed lines in Fig. 3, which shows exposure in terms of hours to better represent the load-follow power operations.
Figures 4 and 5 show results for fuel-clad gap thickness and maximum clad hoop stress, respectively. Each figure contains 2D results for four statepoints, all of which were created with the VERAView graphical user interface (GUI) [13]. For clarity, the colorbar legend for each plot is enlarged and shown on the right. 3D distributions of data are available in Ref. 12, but only 2D data are shown here for brevity.

In both figures, assembly locations B-9 and G-14 each have 8 rods that demonstrated convergence issues, so they are missing data and are denoted with white, similar to guide tubes. Inputs for these rods were communicated to the BISON team and are the subject of ongoing discussions to resolve the issues they posed. However, the rods do not seem to be limiting based on power distribution.

Figure 4 shows the gap thickness. From State 1 (HZP), fresh assemblies are denoted in red to distinguish them from burned assemblies. Effectively, the roughly 69.5 micron gap is the result of the rod’s thermal expansion, closing a bit from the fabricated gap thickness. Distributions on the burned assemblies can be seen as a result of their power profiles from Cycle 2 (or Cycle 1 in the case of H-8). By State 7, the gap has closed in nearly all burned assemblies, and even fresh assemblies are experiencing significant closure, if not full contact. States 13 and 90 look pretty similar, with many rods experiencing contact except for some rods near the periphery. The full set of results [Ref. 12, Appendix B], shows that, as power changes from high to low, some rods that are in contact experience a small amount of lift-off, and contact is not maintained.

Fig. 4. Quarter-core test – fuel-clad gap thickness (μm).

Figure 5 shows the max clad hoop stresses. At beginning of cycle (BOC), many of the stresses are negative, though all are very small. The fresh assemblies and rods not experiencing any contact demonstrate negative stresses because of the difference between the higher system pressure and the lower rod internal pressure. The burned assemblies have some fission gas produced from previous operation, so their rod internal pressures are higher than the fresh assemblies, leading to either positive or less negative hoop stresses. At State 7, some of the burned assemblies demonstrate some considerable hoop stresses (~80 MPa), but nothing alarmingly high and quite comparable to those observed during nominal operations. Many fresh assemblies still have not experienced much contact at this stage, so stresses remain negative. In State 13, many higher stress locations have relaxed some, as the magnitudes are lower. However, many of the fresh assemblies now have many rods experiencing contact and are showing some notably positive stresses, but still rather low comparatively. During State 90, where power is decreased, the magnitude of hoop stresses drops considerably (as in the single rod demonstration). Ref. 12, Appendix C provides complete results.

VERA-CS calculations for this problem were run on the Panacea cluster at Oak Ridge National Laboratory (ORNL), taking ~7 days on 1,000 cores (~168,000 core-hours). With these numbers, a full cycle might take between 2.5 and 3.0 million core-hours. With additional speed ups planned in MPACT, 1.0–2.0 million is more likely.

The BISON cases were run on the Falcon supercomputer at Idaho National Laboratory (INL), requiring roughly 70,000 core-hours. In general, this performance is much better than expected. Cycle 6–7 results from earlier this year [10] indicate that quarter-core BISON results required roughly 35,000–40,000 core-hours. After nearly quadrupling the number of statepoints in the cycle, it was not unreasonable to expect 120,000–160,000 core-hours, but various improvements made to BISON and CASL’s use of it likely helped to reduce run times.

Fig. 5. Quarter-core test – maximum clad hoop stress (MPa).
CONCLUSIONS

Load-follow simulations with VERA-CS and the one-way coupling to standalone BISON were demonstrated, including a single rod with a full cycle of load-follow operations and a quarter-core model with a single month of load-follow. From the single rod case, no convergence issues were observed in any of the ~1,800 statepoints it simulated. This provided sufficient incentive to proceed with the quarter-core model with a single month of load-follow operations data. This simulation also completed successfully, with only minor issues encountered, though adequate workarounds were typically found. The 16 rods that failed to converge in BISON are part of ongoing discussions with INL personnel that will hopefully have a meaningful impact on the robustness of future cases.

There are some remaining questions regarding the accuracy of the results, but this can be addressed in future analyses. There may also be questions as to whether or not additional statepoints are needed to accurately predict the transient xenon behavior during the load-follow operations. However, the goal of this work was to demonstrate that the VERA tools could simulate these operations; this goal has been accomplished, so Exelon and UIUC can proceed with their simulations with more confidence.

Future work should focus on improving performance and fully incorporating the speedups projected in MPACT. Plans are underway to improve the robustness of the CMFD speedups through incorporation of a multilevel (in energy) CMFD solver. Furthermore, future collaboration between ORNL and the University of Tennessee, Knoxville, (UTK) could hopefully yield substantial improvements specific to load follow. With the current projection of ~2 million core-hours for a full load-follow cycle (compared to 15,000–20,000 for a full cycle of nominal operations), substantial improvements will likely be needed before this is work attractive beyond a research exercise.

Additional information and complete set of results for each statepoint are provided in Reference 12.

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REFERENCES