Watts Bar Nuclear Unit 2 Startup Experience

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INTRODUCTION

The Consortium for Advanced Simulation of Light Water Reactors (CASL) [1] was well positioned in 2016 to perform high-fidelity reactor physics predictions [2,3] of the initial startup of Tennessee Valley Authority's (TVA) Watts Bar Nuclear Unit 2 (WBN2) [4,5]. The WBN2 startup was a major milestone for the US nuclear power industry, which had not put a new plant online for over two decades. This was a significant opportunity for the CASL program to support its industry partners, TVA and Westinghouse Electric Co., with the advanced methods in the Virtual Environment for Reactor Applications (VERA). In addition to providing an excellent source of validation data for VERA, the WBN2 startup also gave TVA and Westinghouse the opportunity to confirm existing design predictions for the plant, gain insights in modeling improvements towards more accurate predictions, and establish additional confidence in a successful plant startup [3].

WATTS BAR NUCLEAR UNIT 2

TVA's WBN2 achieved initial criticality on May 23, 2016 and began full-power commercial operation on October 19, 2016 [4]. It is a traditional Westinghouse 3411 MW_{th} four-loop pressurized water reactor (PWR) with an ice condenser containment design much like that of its sister Unit 1 [3]. Its reactor core consists of 193 nuclear fuel assemblies of the Westinghouse 17×17 design. Cycle 1 was loaded in three enrichment regions, shown in Fig. 1, to minimize the fuel costs of the initial core and optimize the power distribution. While the initial fuel loading pattern is similar to that of other first cycle designs like Watts Bar Nuclear Unit 1 (WBN1), this was the first instance where integral fuel burnable absorber (IFBA) and wet annular burnable absorber (WABA) burnable poisons were used in an initial core. The rod cluster control assemblies (RCCAs) used for reactivity control and reactor shutdown are the typical Ag-In-Cd design used in many Westinghouse plants. A new feature of WBN2 is the use of fixed five-level vanadium in-core detectors, rather than movable fission chambers. For more information on WBN2 please refer to the WBN2 VERA start-up results [3].

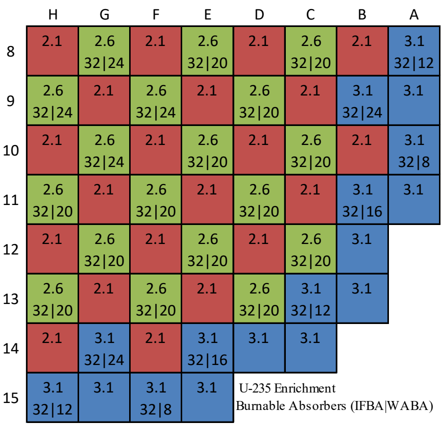

Fig. 1. Watts Bar Nuclear Unit 2 initial core loading pattern shown in quarter-core symmetry.

VIRTUAL ENVIRONMENT FOR REACTOR APPLICATIONS

In 2016, VERA was already setting the standard for high-fidelity multi-physics simulations of PWRs. CASL had completed validation activities based on twelve fuel cycles of data from WBN1 [6] and had begun benchmarking activities on nearly a dozen other plants. The VERA tools were still maturing but had already demonstrated the accuracy and reliability needed for the WBN2 analyses prior to the startup. The primary components of VERA 3.6 employed for these analyses were:

- **MPACT**: An advanced pin-resolved whole-core multi-group deterministic neutron transport capability based on the 2-D/1-D synthesis method [7], using 51 energy-group, ENDF/B-VII.1 cross sections and the subgroup method of on-the-fly resonance self-shielding [8].
- **CTF**: An advanced subchannel thermal-hydraulics capability using a transient two-fluid, three-field (i.e., liquid film, liquid drops, and vapor) modeling approach to determine the thermodynamic conditions in every coolant channel in the core, including cross-flow effects from turbulent mixing and lateral pressure gradients [9].

This manuscript has been authored by UT-Battelle, LLC, under Contract No. DE-AC0500OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

- **ORIGEN**: An isotopic depletion and decay code capable of generating source terms for accident analyses, characterizing used fuel (including activity, decay heat, radiation emission rates, and radiotoxicity), and activating structural materials [10].

In addition, the Shift Monte Carlo neutron transport code [11] was used to generate neutronic reference solutions prior to the startup, and the BISON fuel performance code [12] was used to generate fuel temperature correlations as a function of fuel rod power and burnup in the analysis. For more information on these contributions, please see the WBN2 VERA start-up results [3]. (Note: the current CTF fuel rod modeling capability was not available at the time of this work.)

PRE-STARTUP ANALYSES

Approximately six months before the initial criticality of WBN2, CASL began developing VERA models for the new reactor core, based on the latest cycle design information and as-built specifications. The models were developed cooperatively by TVA, Westinghouse, and Oak Ridge National Laboratory (ORNL). Westinghouse also provided the results from their analyses for the startup, using their in-house reactor physics code system for comparison. High-performance computing (HPC) was provided by the Oak Ridge Leadership Computing Facility (OLCF) [13] and the High-Performance Computing Center at Idaho National Laboratory (INL) [14] for VERA simulations.

VERA calculations of initial criticality and startup physics parameters were performed prior to the startup, and the results were compared to additional results from the Shift and Westinghouse methods. On March 1, 2016, an internal memo was provided to all involved parties officially documenting the VERA results for startup parameters [3, Appendix A]. As a result of these and subsequent results and discussions, Westinghouse made several modeling improvements to their original model:

1. A calculated control bank worth (human) error was identified prior to the startup.
2. Westinghouse implemented improved modeling of WABAs, including explicit geometry of non-poison axial regions which were not previously included in the WBN2 models.
3. Westinghouse identified use of the older ENDF/B-VI.3-based cross section library used in their original calculations as an additional contributor to initial differences in startup reactivity.

In general, the predicted results from VERA were very similar to those from the existing industry methods, with differences being less than the typical acceptance criteria for each startup test. As a result of this activity and the availability of an independent, high-fidelity capability for modeling the future startup conditions, both Westinghouse and TVA gained additional insight and confidence in the upcoming plant startup testing. Furthermore, independent analyses were requested for shutdown margin and xenon transient stability calculations using the VERA models, providing an alternate set of data for answering questions TVA and Westinghouse had at the time. As time passed, all of the VERA calculations were confirmed by actual measurements from the plant.

STARTUP PHYSICS TESTING

WBN2 achieved initial criticality on May 23, 2016, with a critical boron concentration of 1,089 parts per million boron (ppmB). This was 17 ppmB above the original VERA prediction, adjusted for measured ^{10}B content, and well within the typical 50 ppmB acceptance criteria. Since then, more recent VERA versions have resulted in differences of 2 ppmB (VERA 3.6) and even 0.4 ppmB (VERA 4.1). Newer versions include minor improvements in cross sections and changes to fix various software defects.

The measured hot zero power (HZP) isothermal temperature coefficient (ITC) for WBN2 was -5.3 pcm/°F, which was 0.8 pcm/°F more positive than the VERA prediction and less than the typical 2 pcm/°F acceptance criteria. More recent VERA versions produce the same difference (VERA 3.6) and 0.7 pcm/°F (VERA 4.1).

Finally, TVA measured the reactivity worth of each RCCA bank using the dynamic rod worth measurement (DRWM) method. The largest percent error between any individual bank worth and those initially predicted by VERA was 3.4%, with error in the total bank worth of 1.4%. More recent VERA versions improved agreement with a maximum error of 3.0% and a total error of 0.7% (VERA 3.6), and the most recent VERA release version (VERA 4.1) reduced the total error further to 0.5%. The individual bank worth differences are shown in Fig. 2.

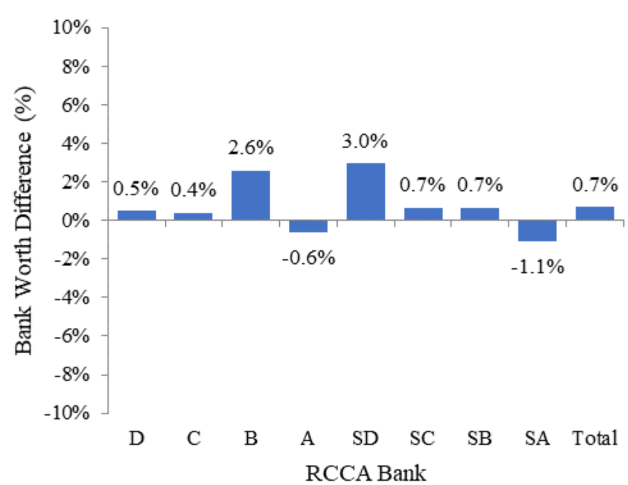

Fig. 2. Hot zero power RCCA bank worth comparisons.

POWER ASCENSION TESTING

Power ascension to full-power commercial operation consisted of more than five months of testing, including both planned and unplanned periods of reactor shutdown. The reactor power history for this interval is shown in Fig. 3. VERA simulations were performed by the hour based on detailed reactor operating data provided by TVA. HPC resources at the Oak Ridge Leadership Computing Facility (OLCF) [11] and the High-Performance Computing Center at Idaho National Laboratory (INL) [12] were utilized. In total, 35 jobs comprising 4,130 statepoints, with 16,605 fully converged neutronic and thermal-hydraulic iterations, required approximately 13.5 days on an average of 2,784 computing cores—approximately 900,000 core hours for the entire simulation. The WBN2 VERA start-up results [3] provide detailed hourly data for relevant reactor parameters such as power, control bank positions, inlet coolant temperature, average coolant temperature, and axial flux difference (AFD).

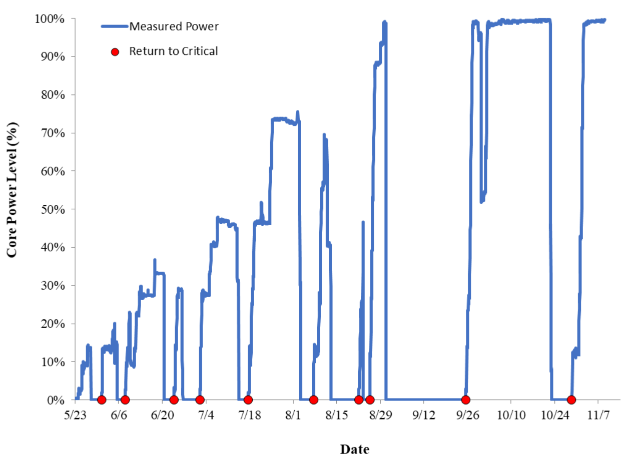

Fig. 3. Reactor startup power history.

Hot Zero Power Criticality

During the power escalation process, ten additional hot zero power criticality measurements were taken following periods of reactor shutdown, shown as red circles in Fig. 3. The outage lengths varied from approximately 2 to 25 days, providing a variety of transient fission product conditions for comparison. The VERA results for these statepoints were compared to measurements and are shown in Fig 4, with an average critical boron difference of -7 ppm. This result demonstrates that VERA provides excellent isotopic depletion and decay capability for extended or repeated transient and shutdown scenarios, at least in the low fuel burnup regime.

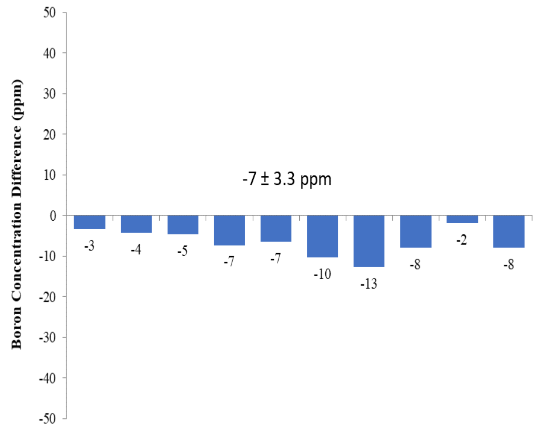

Fig. 4. Hot zero power critical boron differences for each post-shutdown criticality measurement.

Power Distributions

In-core flux distributions in WBN2 are measured using a fixed, self-powered, in-core detector system. These detectors consist of vanadium wire emitters which generate an electrical current from beta decay following neutron absorption by ^{51}V. Each of the 58 detector locations (shown in Fig. 6) consists of five wires of different lengths proportional to the active fuel height. The sensitive region of the longest wire essentially corresponds to the entire fuel stack, while the shortest wire is only sensitive to the bottom 20% of the fuel assembly.

MPACT provides the in-core detector response by calculating the ^{51}V neutron absorption rate in each of the detector locations at all axial planes in the model. This high-fidelity response was then postprocessed by cubic spline fit and subsequent integration onto the elevation boundaries of the five vanadium wires. The longest wire, for instance, is calculated by integrating along the entire axial fuel stack, while the shortest wire is only integrated from the bottom up to about 20% of the active fuel stack. Figure 5 demonstrates this processing, displaying the original MPACT detector response for a single core location, overlaid with the curve fit and subsequent integration into five levels.

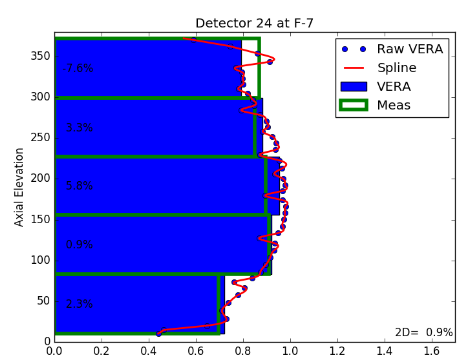

Fig. 5. Example detector response processing for the five-level vanadium detector comparisons.

During WBN2 power ascension and subsequent full-power operation, twelve sets of measured in-core detector signals were analyzed and compared to VERA calculations. These "flux maps" were provided by TVA from the WBN2 online monitoring system at various burnups and power levels, including maps at 27, 40, 47, 74, 88, and 100% of rated power. RCCA Bank D positions also varied from 185 to 220 steps withdrawn.

For each map comparison, the measured and calculated detector response distributions were normalized and compared via percent difference (*(C – M) × 100*) and root mean square (RMS) difference. Several methods were utilized and are presented in the WBN2 VERA start-up results [3]; but for brevity this document presents the detector wire current analysis, in which the radial distribution comparisons are made based only on the long detector wires, and the total distribution comparison is based on integrated reaction rates for each of the five wires in each location. Figure 6 provides an example comparison of long wires from the last of the twelve flux maps, in which the standard deviation is approximately 2%. Figure 7 also demonstrates the comparison analysis for each of the five wire lengths for all core locations, in which the standard deviation ranges between 2 and 2.5% for all wires.

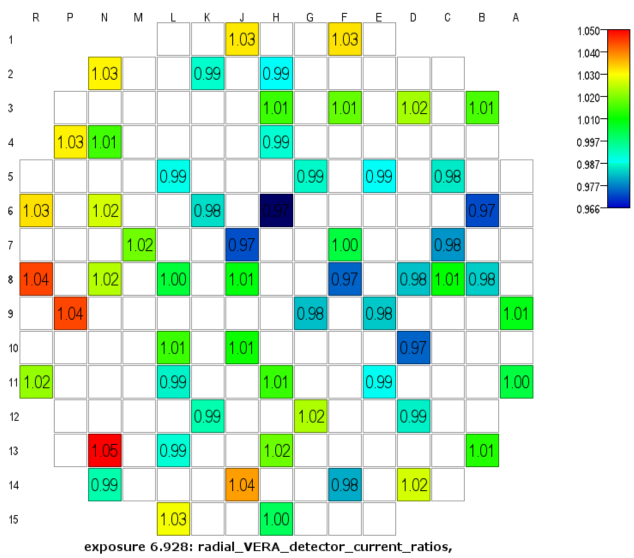

Fig. 6. Ratio of calculated to measured relative currents in the long vanadium wire in each measured location.

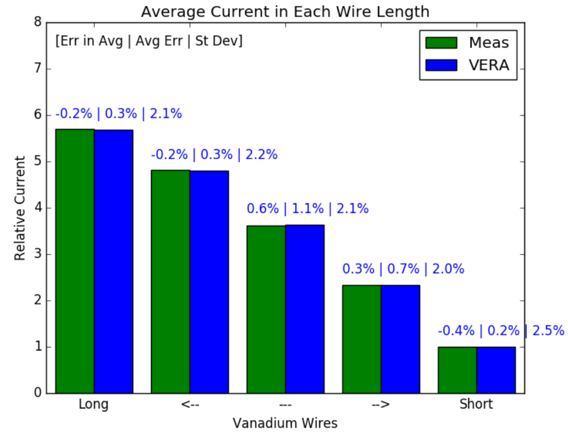

Fig. 7. Comparison of average current in each vanadium wire length.

The results of the in-core power distribution comparisons were excellent. Larger deviations were observed, as expected, in the shorter wires and at lower power levels, when the uncertainty in the measurements from the self-powered detector system is larger. Over all twelve cases, the RMS of the differences in currents in all wires was 3.3%, and the RMS of the differences in long wires (i.e., representing just the radial power shape) was 2.2%. These results are shown in Fig. 8.

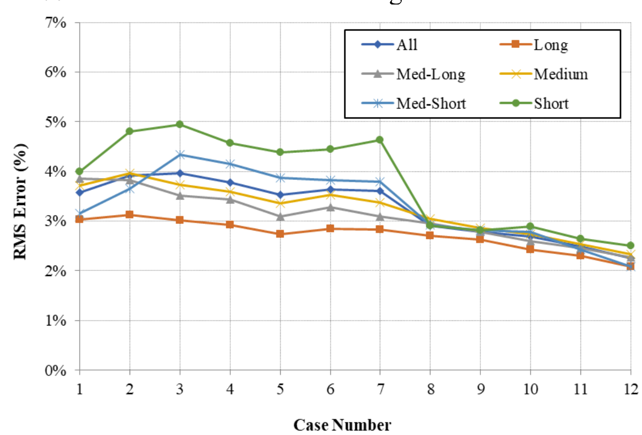

Fig. 8. Statistical summary of the RMS error in the relative detector current for all cases.

Axial Flux Difference and Fuel Temperatures

The measured AFD from the WBN2 ex-core detectors was provided by the hour and compared to the calculated in-core values by VERA. AFD is calculated as the following:

$$AFD = \frac{P_{Top} - P_{Bottom}}{P_{Top} + P_{Bottom}} \times \%FP$$

where P_{Top} and P_{Bottom} are the ex-core signals in the top and bottom sensors, respectively, and *%FP* is the percent of rated thermal power of the core. In most cases, agreement was good with an expected bias (due to the measurement being ex-core). However, for periods of power plateaus following power escalation, a severe oscillation was observable in the VERA solution. An example is shown in Fig. 9. In the worst cases, the VERA AFD would diverge unphysically. In reactor physics, this behavior is characteristic of an underpredicted Doppler reactivity worth, which acts as a dampener during what are known as *axial xenon oscillations* in PWRs.

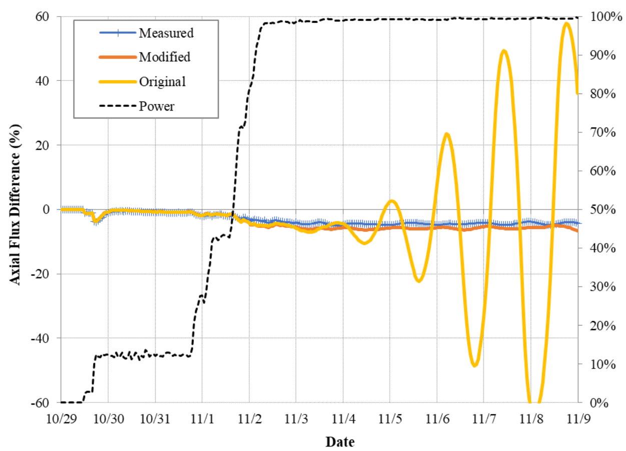

Fig. 9. Divergent AFD oscillations from VERA using original and modified fuel temperature models from BISON.

To obtain more accurate results, the volume-average fuel temperature response as a function of power was artificially increased to provide an improved dampening of this axial power oscillation. The BISON-based temperatures were based on a quadratic function of power for each burnup interval, resulting in decreased response at higher power levels. The modified temperatures were assumed to be linear with power, resulting in an average fuel temperature increase of approximately 50 K, and an increase of about 250 K for local rods at about twice the core average power level. For details on this approximation please refer to the WBN2 VERA start-up results [3].

The fuel temperature modification resulted in significant improvement in core axial power shape (see *modified* data in Fig. 9) during long periods of steady state operation. However, the change degraded both the critical boron concentration and the radial power distribution predictions compared to the measured data. More research is needed to identify the reason for this axial instability. In particular, the fuel temperatures generated by BISON need additional validation to ensure accuracy and consistency in the nuclear feedback response to MPACT. The resulting AFD comparisons for a subset of the power ascension cases are provided in Fig. 10. Though the AFD does not diverge, the calculated oscillations are still observably larger than the corresponding measurements.

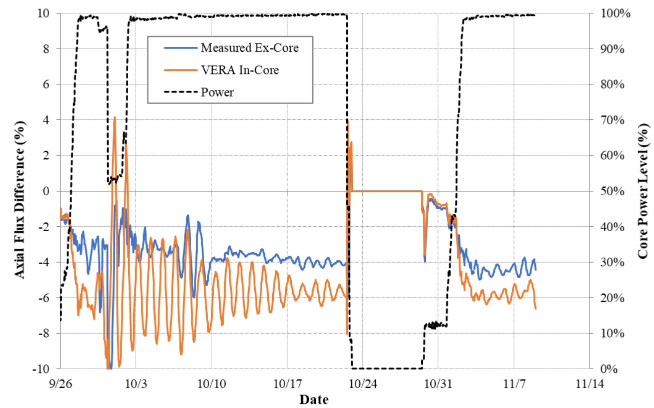

Fig. 10. Calculated and measured AFD comparison near hot full power using modified BISON fuel temperatures.

At-Power Critical Boron Concentrations

Measured at-power soluble boron concentrations from the plant reactor coolant system were provided by TVA and adjusted for ^{10}B depletion effects. Approximately 200 measured data points representing critical conditions were compared with VERA over the greater than 4,000-hour simulation. The results were inconsistent with the hot zero power results, with larger negative differences. VERA underpredicted the at-power reactivity by -37 ± 11 ppmB, which is still within the typical 50 ppmB acceptance criteria, but larger than the hot zero power cases. This was attributed to the modified BISON fuel temperatures, which were artificially increased at higher powers to provide stronger axial dampening in the AFD oscillations. This effect is further highlighted in Fig. 11, which demonstrates a reactivity bias that increases as a function of core power level, which is consistent with the direction of modified fuel temperatures. More research is needed to determine a resolution that results in improvement in AFD stability without degrading at-power reactivity prediction.

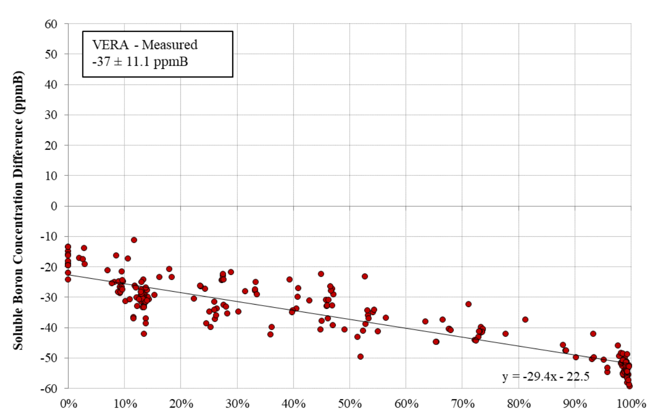

Fig. 11. Critical boron concentration differences as a function of core relative power level.

CONCLUSIONS

The startup of a new nuclear power plant in the United States was an excellent opportunity to apply CASL's high-fidelity virtual reactor, VERA, and it was especially beneficial that the plant owners, manufacturer, and fuel vendor were core partners in the CASL consortium. Following VERA initial capability development and benchmarking of the WBN1 reactor, the startup analysis of Unit 2 was a significant achievement for CASL, showing VERA's technical and programmatic relevance to the commercial nuclear power industry by providing an advanced and predictive methodology.

The WBN2 startup simulations and subsequent analyses demonstrated the value of VERA as a high-fidelity, easy-to-use predictive tool for new reactor startups and first-of-a-kind evolutions. CASL's predictions for physics testing were provided three months in advance of the reactor startup and were proven very accurate. VERA shows virtually perfect agreement with the initial critical boron measurements of -2 ppm, and total control bank worth errors of less than 1%. The in-core power distribution comparisons were also excellent, with full-power maps showing agreement with 2–3% RMS for all detector wires. Additionally, the advanced methods employed by VERA were able to provide insight for the WBN2 startup that improved existing industry methods.

This activity demonstrated the broad value in direct collaboration among the plant operator, fuel vendor, and national laboratory. The success of CASL has not been in its products alone, but also in bringing together its members to share data, expertise, and computational resources within a collaborative environment for the benefit of the entire nuclear industry.

ACKNOWLEDGMENTS

The authors acknowledge the many contributors from CASL partner organizations that enabled the success of this milestone, particularly John Ritchie, Steven Halcomb, and Christine Setter of TVA, as well as David Salazar, Vefa Kucukboyaci, and the late Jeffrey Secker of Westinghouse. The authors also wish to acknowledge the many developers of VERA who spent many years in CASL working to improve the accuracy, performance, and usability of VERA, including Ben Collins, Tom Downar, Tom Evans, Cole Gentry, Aaron Graham, Dan Jabaay, Brendan Kochunas, Ron Lee, Scott Palmtag, Tara Pandya, Bob Salko, Shane Stimpson, and most importantly Jess Gehin. This research also made use of the Oak Ridge Leadership Computing Facility at the ORNL, which is supported by the Office of Science of the US Department of Energy under Contract No. DE-AC05-00OR22725, as well as the High-Performance Computing Center at INL, supported by the Office of Nuclear Energy of the US Department of Energy under Contract No. DE-AC07-05ID14517.

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