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Analysis of the Startup of Watts Bar Nuclear Unit 2 using VERA

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Abstract - *The Consortium for Advanced Simulation of Light Water Reactors (CASL) has applied its advanced reactor simulation capability, the Virtual Environment for Reactor Applications (VERA), to successfully model the initial startup of Tennessee Valley Authority's (TVA) Watts Bar Nuclear Unit 2. This was a unique opportunity to use VERA's high-fidelity multi-physics capability prior to the first commercial reactor startup in the United States in two decades. With CASL partners TVA and Westinghouse, and with the assistance of the High Performance Computing Facility at Idaho National Laboratory, predictions were prepared before the startup which corroborated the results from the design licensed methods and were later confirmed by measured plant data. Additionally, with support from the Oak Ridge Leadership Computing Facility, the VERA tools were used to follow the entire power ascension sequence to commercial operation, through all power ramps, load reductions, and outages, with comparisons of measured core reactivity and in-core power distributions. This unique activity represents the largest single simulation for CASL to date for an important and rare event for TVA, Westinghouse, and the entire nuclear power industry.*

I. INTRODUCTION

The Consortium for Advanced Simulation of Light Water Reactors (CASL) [1] continues to improve and validate the suite of high-fidelity software and methods known as the Virtual Environment for Reactor Applications (VERA). It includes reactor physics methods, solvers, and multi-physics coupling algorithms that provide the most advanced commercial power reactor simulation capability available, including directly coupled 3-dimensional (3-D) neutronics, sub-channel thermal-hydraulics (T/H), and in-line isotopic depletion and decay. This capability has been demonstrated through a rigorous benchmark of 20 years of operation of Watts Bar Nuclear Unit 1, a traditional Westinghouse four-loop pressurized water reactor (PWR) operated by the Tennessee Valley Authority (TVA) [2,3].

TVA's Watts Bar Nuclear Unit 2 (WBN2) is the first commercial power reactor to go on-line in the United States in two decades. It achieved initial criticality on May 23, 2016; and, following power ascension testing, declared full power commercial operation on October 19, 2016 [4]. For this important event, CASL was perfectly positioned to perform high-fidelity startup predictions and detailed core follow calculations coinciding with the 5 month power ascension testing period. The partnerships between Oak Ridge National Laboratory (ORNL), Westinghouse Electric Co., and TVA have been critical to the success of CASL and, through continued data exchange and applications, ensure that VERA will be valuable for the nuclear power industry.

In this document, the VERA results for the WBN2 startup and power ascension are compared with measured plant data, including criticality measurements, control bank reactivity worths, isothermal temperature coefficients, and measured in-core power distributions. Together, these results demonstrate continued advancements in VERA, a broadened application space, and an increased robustness and confidence in the CASL tools.

Additionally, the computational performance of VERA is demonstrated for a very large and realistic simulation of a commercial plant that is undergoing significant and continuous changes in power, temperature, control rod positions, and fission product poisons distributions. Although VERA's performance continues to be improved, these results represent another major achievement for CASL.

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II. WATTS BAR NUCLEAR UNIT 2

WBN2 is a traditional Westinghouse four-loop 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 in a cylindrical arrangement. Cycle 1 is loaded in three enrichment regions to minimize the fuel costs of the initial core and optimize the power distribution. While the initial fuel loading pattern is similar to that in other first cycle designs like WBN1 (Fig. 1), this is the first instance with integral fuel burnable absorber (IFBA) and wet annular burnable absorber burnable (WABA) poisons. 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 around the globe. Another new feature of WBN2 is the use of fixed five-level vanadium in-core detectors, rather than moveable fission chambers. It is initially rated at 3411 MW_{th}, and the fuel assembly, RCCA bank locations, and in-core detector locations in WBN2 are the same as in WBN1, shown in Reference 2.

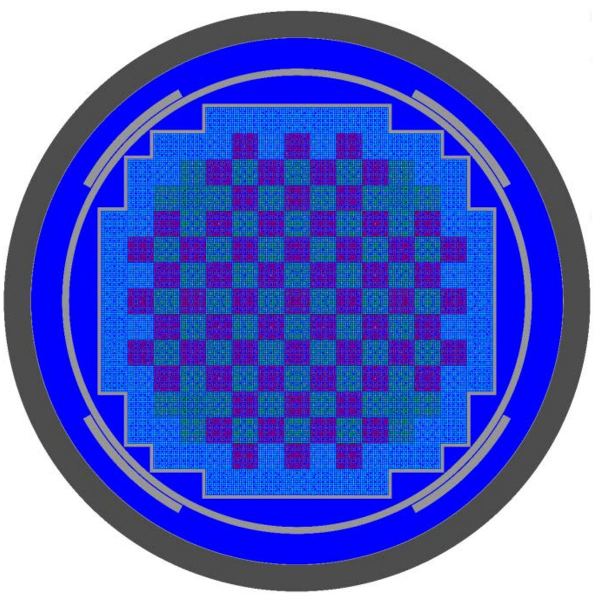

Fig. 1. General radial layout of the WBN2 reactor core [2].

III. VIRTUAL ENVIRONMENT FOR REACTOR APPLICATIONS

The state-of-the-art capabilities within VERA provide unprecedented resolution for reactor analysis through high-fidelity multi-physics couplings. The components for steady-state reactor core simulation have been selected to eliminate barriers facing modern industrial methods for improved accuracy on smaller spatial scales. VERA provides direct and fully coupled solutions at the fuel rod level for neutronics and T/H without any spatial homogenization. Isotopic depletion and transmutations occur locally within the once-through 3-D calculation, avoiding the need for macroscopic spectral corrections to simplified history models. The user interface is designed for ease of use and provides a single common geometry model to each of the underlying physics codes. VERA also manages the calculation flow, data transfer, and solution convergence between methods automatically, and it is capable of computational scaling from leadership-class supercomputers (hundreds of thousands of computing cores) to engineering-grade compute clusters (fewer than a thousand cores), enabling access for scientists and engineers across many application areas. The individual physics methods employed by this application of VERA are the following:

MPACT: An advanced pin-resolved whole-core multi-group deterministic neutron transport capability based on the 2-D/1-D synthesis method, on the frame of a 3-D coarse mesh finite difference method, for which axial and radial correction factors are obtained from 2-D method-of-characteristics and 1-D P_N in the axial direction [5]. The transport is performed using 51-energy-group cross sections, based on the subgroup method of on-the-fly resonance self-shielding [6]. The discretization of the core is typically 56 flat source regions per fuel rod at each of approximately 60 axial planes, explicitly treating such features as spacer grids, fuel and absorber plenums, and end plugs. MPACT also controls the functional application features of VERA, such as critical boron search, equilibrium xenon, predictor-corrector depletion, in-core detector response calculations, reading and writing restart files, and performing fuel shuffling and discharge.

CTF: An improved version of the COBRA-TF sub-channel T/H code that uses 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. A wide range of flow-regime-dependent closure models are available for capturing complex two-phase flow behavior, which includes rod-to-fluid heat transfer, inter-phase heat and mass transfer, wall and inter-phase drag, and spacer-grid-droplet breakup [7].

ORIGEN: A directly coupled isotopic depletion and decay code in the SCALE 6.2 [8] package with 40 years of application bases. It is capable of generating source terms for accident analyses, characterizing used fuel (including activity, decay heat, radiation emission rates, and radiotoxicity), and activating structural materials [9]. VERA uses a modern application programming interface (API) for ORIGEN to enable simulation of the fuel depletion and decay of 263 isotopes in approximately 7.8 million unique regions of the WBN2 reactor core. This implicitly includes the transient Xe-135 calculations required to accurately simulate the detailed fission distribution in the reactor during power maneuvering conditions. This capability also enables direct treatment of all important decay products that can impact core reactivity during repeated short-term shutdowns like those needed for this initial startup testing.

Shift: A massively parallel, continuous-energy Monte Carlo radiation transport code within VERA that employs a high-speed internal geometry package for light water reactors (LWRs) for solving both multi-group and continuous-energy neutron, photon, and coupled neutron-photon transport problems. Both fixed-source and eigenvalue solutions can be obtained for the reactor with detailed fission rate tallies on the same rod-wise mesh used by MPACT, and using the same VERA common input file as well [10]. Development is now underway to directly couple Shift to MPACT to enable the exchange of isotopics, T/H conditions, and ex-core neutron and gamma flux distributions.

BISON: A fuel rod performance code for calculating the fuel thermomechanical behavior during normal operation and transients of LWRs, based on the Multiphysics Object-Oriented Simulation Environment (MOOSE) framework developed at Idaho National Laboratory (INL). MOOSE is a massively parallel finite element computational system that uses a Jacobian-free, Newton-Krylov method for solving partial differential equations. BISON leverages the MOOSE capabilities to model a single fuel rod in 2-D full-length R-Z or planar R-Theta geometric representations, as well as local effects 3-D models [11,12].

The fuel mechanics coupling between BISON, MPACT, and CTF is still under development. For this analysis, BISON was used to pre-generate correlations of volume-average fuel temperature as a function of fuel rod linear heat rate and exposure, which are used by MPACT to determine the local fuel rod temperature at all locations in the reactor.

IV. SIMULATIONS AND ANALYSES

Before initial criticality, the CASL team obtained the necessary data to build VERA models and perform a predictive analysis of the WBN2 startup and physics testing. These results were compared with predictions from licensed design methods and were shown to agree well within the acceptance criteria of the startup tests. This provided additional confidence for the startup; subsequently the quality of the predictions was confirmed by the TVA measurements (shown below).

The startup physics tests were performed at WBN2 after initial criticality and included RCCA bank reactivity worth measurement via the dynamic rod worth measurement technique, and measurement of the isothermal temperature coefficient. Additional calculations were performed as desired for other quantities of interest, such as shutdown margin and predictions of the fuel cycle length.

As WBN2 performed power ascension testing, detailed inputs were created and executed to follow the hourly power, temperature, and control rod history of the reactor, including all intermediate shutdowns. The power, regulating bank, and soluble boron histories of the startup are shown in Figures 3, 4, and 5, respectively. During the process, ten additional reactor shutdowns occurred, the ninth of which lasted approximately 25 days. The total simulation consists of 4,130 statepoints for approximately 177 days of operation, resulting in the largest reactor simulation ever performed by CASL.

One set of hourly power ascension simulations were performed using the Oak Ridge Leadership Computing Facility's (OLCF) moderate-sized high performance computing (HPC) resource Eos. Eos is a 736-node Cray XC30 cluster using Intel Xeon processors and Cray's Aries Interconnect and Dragonfly Topography. Each node has 16 physical cores and 64 GB of memory. Intel's Hyper-Threading technology allows each core to work as two logical cores [13].

The VERA cases for power ascension incorporated the full coupling available between MPACT, CTF, and ORIGEN. For MPACT, spatial decomposition was employed in quarter-core symmetry using 58 axial planes and 48 radial domains for a total of 2,784 processors. CTF solved each quarter-assembly in parallel on 193 processors. The required 4,130 statepoints were executed using 35 independently executed jobs connected by restart files, in total requiring 13.6 days of wall time and approximately 900,000 core-hours. Convergence for all statepoints required 16,605 total coupled neutronic-T/H iterations, resulting in an average runtime of 4.8 minutes per statepoint. Figure 2 provides the approximate breakdown in run time between the three major coupled physics components.

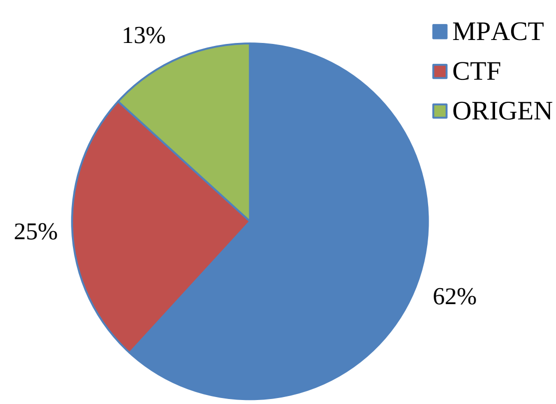

Fig. 2. Approximate run time percentages for each physics component.

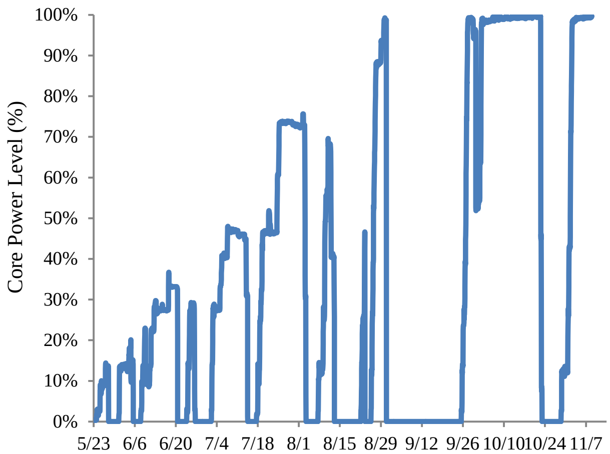

Fig. 3. WBN2 startup power history.

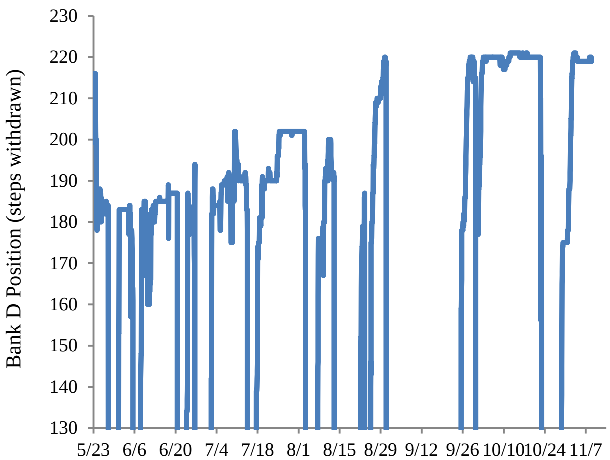

Fig. 4. WBN2 startup regulating bank position history.

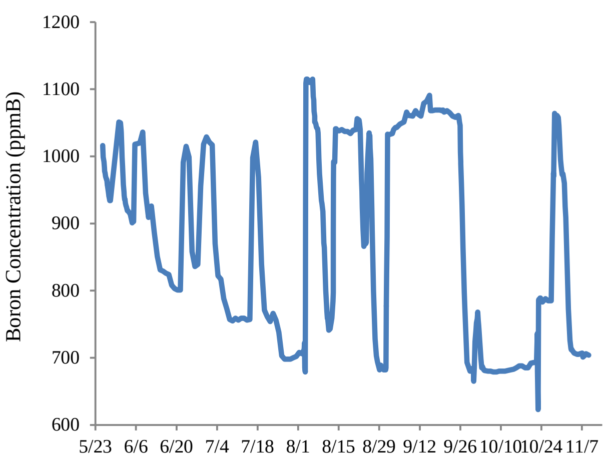

Fig. 5. WBN2 startup soluble boron history.

The hourly follow calculations provided very accurate time-dependent distributions of the short-term fission products such as Xe-135 and Sm-149. Unlike traditional industrial methods, VERA is capable of easily tracking all important transient fission products through the entire startup scenario, including the ten periods of shutdown decay, and does so in nearly 2 million unique regions in the reactor core. This is evident in the consistency of the return-to-critical boron concentration comparisons in the Results section.

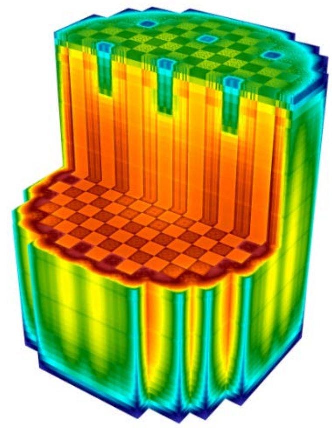

Fig. 6. 3-D Rod-by-rod transient xenon-135 distribution at 28% power plateau calculated by VERA (via ORIGEN).

V. RESULTS

1. Initial Criticality and Physics Testing

WBN2 achieved initial criticality by boron dilution and Bank D withdrawal at hot isothermal conditions. VERA results for this configuration were excellent. The critical boron concentration calculated by MPACT at the critical rod position was only 2 ppmB below the measured value, and the eigenvalue calculated by Shift for the critical conditions was only 22 pcm below critical.

The comparison between the measured and predicted isothermal temperature coefficients was acceptable, with a difference of –0.8 pcm/°F.

The measured RCCA bank reactivity worths also demonstrated excellent agreement with VERA predictions, with an average bank worth difference of 0.7% and a maximum difference in any bank of 3.0%. These are provided in Figure 7.

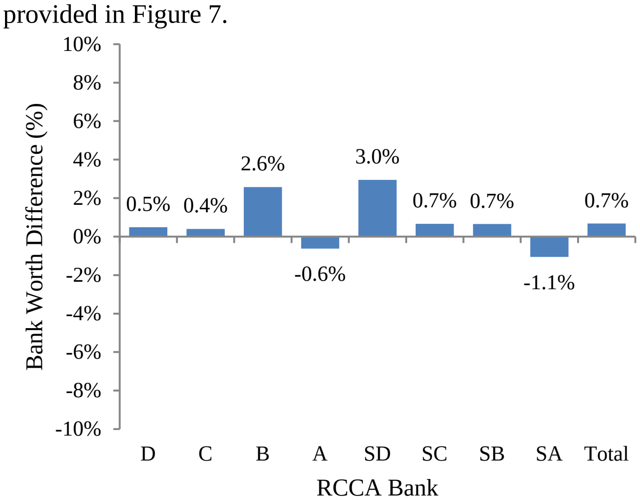

Fig. 7. Hot-zero-power control bank worth comparisons.

2. Return-to-Critical Boron Concentrations

VERA was used to calculate the critical soluble boron concentration for each instance when WBN2 returned to criticality following a period of being shut down. With the exception of the 25 day outage, these shutdown periods ranged from 2 to 9 days and covered a range of burnups, rod positions, and transient fission product distributions. The reactivity calculated by MPACT was very similar to the values measured by the plant, with an average difference of −6 ppmB (MPACT under-predicted the reactivity) and a standard deviation of 3.4 ppmB. These values, shown in Figure 8, demonstrate a consistently low reactivity prediction compared with the plant.

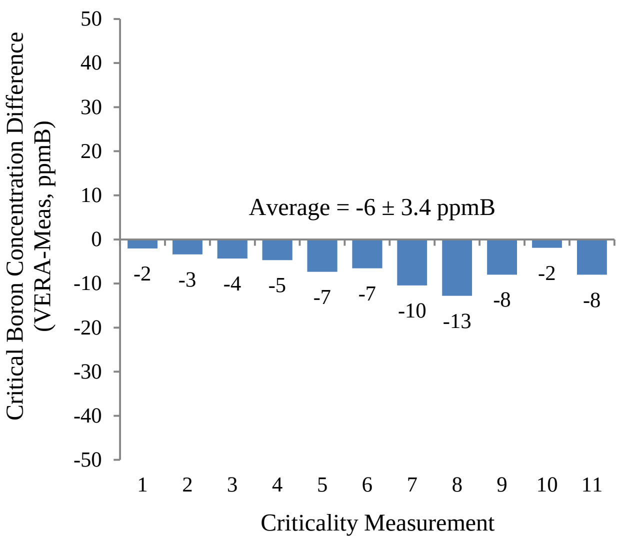

Fig. 8. Return-to-critical hot-zero-power critical boron comparisons.

3. Power Ascension Testing

During the 5 months of testing between initial criticality and beginning commercial operation, WBN2 took more than 300 boron samples from the primary coolant system. Of these, about 200 were taken while the reactor was critical and operating above zero power. These measurements were compared with the critical boron concentrations calculated by VERA for the entire power ascension sequence of 4,130 statepoints, matching both power and control rod positions. The differences between measurement and VERA-calculated values for all of the conditions analyzed to date are shown in Figure 9. The average difference is –37 ppmB, much larger than the zero power results, and the standard deviation is 11 ppmB, which indicates increased uncertainty, or error, for conditions with increased temperature and xenon concentration. An increasing error trend is observable in both burnup and power, indicating a possible error in the predicted power defect, likely due to the fuel temperature model chosen for this simulation.

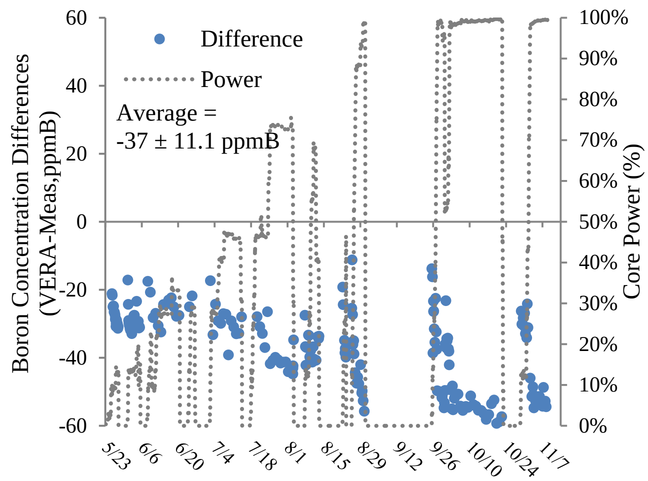

Fig. 9. Power ascension critical boron differences.

During power escalation, comparisons of the measured signals from the in-core vanadium detectors were compared with the instrument responses calculated by VERA. MPACT includes the capability to calculate the normalized reaction rates for several detector types at user-specified locations in the reactor core. To map the calculated responses onto the 5-level axial mesh of the WBN2 detectors, a cubic spline was used to fit the fine mesh axial distribution; then the results were calculated with axial integration, taking into account the individual lengths of the vanadium wires. Additionally, the VERA cases for the flux maps comparison were run in full core geometry with explicit inclusion of the in-core detector thimbles and with removal of the WABA rodlets in locations of the primary neutron sources. The results were compared directly with the processed instrumentation signals from the online core monitoring system.

TVA provided twelve flux maps for comparison, the last four of which represented nominal cases for comparison at equilibrium conditions. Three of the radial power distribution comparisons are shown in Figures 10, 11, and 12. In each case, the radial, axial, and total root mean square (RMS) difference is reported in terms of percentage. These values are reported in Table 1.

The five-level vanadium response distribution comparisons indicated several yet unexplained issues. First, at lower powers, both a nonsymmetrical radial tilt and poor axial agreement resulted in a large total RMS difference of 5.4%. This seemed to decrease as power was increased (a phenomenon that is not uncommon). The later distributions showed a closer comparison, owing to conditions approaching equilibrium, and the final map was quite good with a radial RMS of 1.9% and total RMS of 3.2%. Additionally, the final deviation in total detector currents is only 0.5±2.2%.

Although some questions remain about the vanadium detector comparisons, and research will continue into understanding these differences, the power distribution results, especially at the higher core powers, provided excellent validation for VERA against measured data from a challenging time-dependent plant evolution.

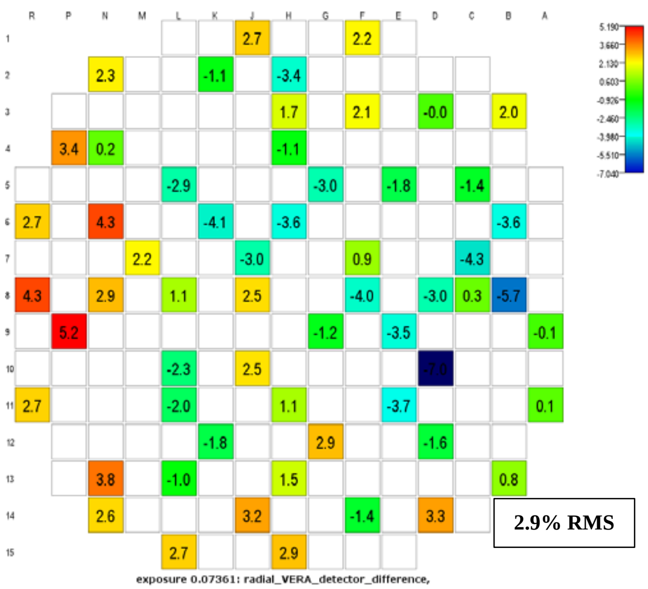

Fig. 10. Radial instrument response differences (%) at 27% power.

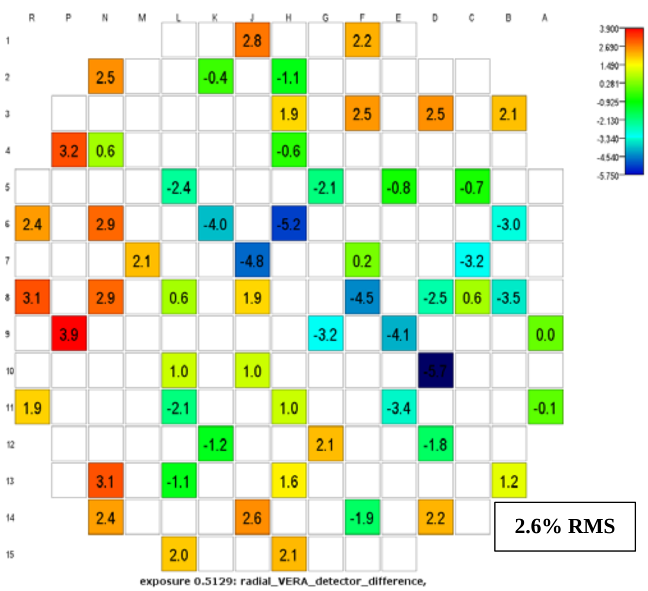

Fig. 11. Radial instrument response differences (%) at 74% power.

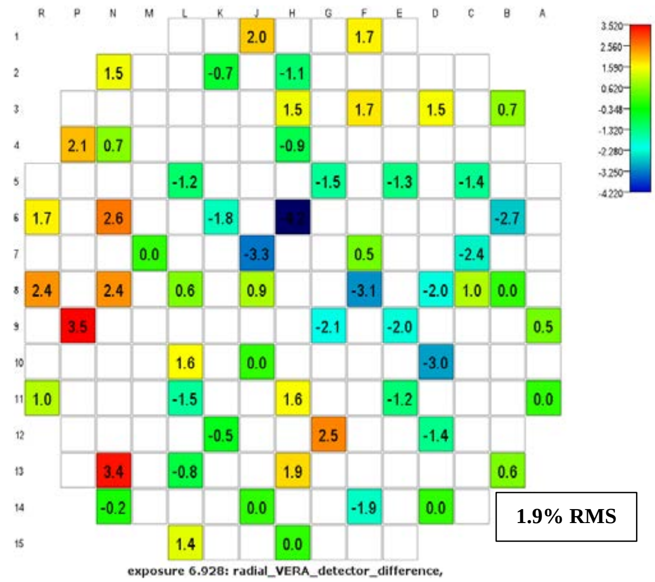

Fig. 12. Radial instrument response differences (%) at 100% power and equilibrium conditions.

Table I. In-core Instrument Response Distribution Statistics

Map	Burnup (GWd/MT)	Power	Bank D Pos.	Radial RMS	Axial RMS	Total RMS
1	0.1	27%	185	2.9%	3.1%	5.4%
2	0.1	28%	185	3.0%	3.9%	6.0%
3	0.2	40%	189	2.8%	2.9%	4.9%
4	0.3	47%	191	2.8%	2.4%	4.5%
5	0.5	74%	202	2.6%	2.8%	4.5%
6	0.9	88%	210	2.7%	2.2%	4.2%
7	1.0	99%	219	2.6%	2.7%	4.3%
8	2.0	99%	221	2.6%	1.6%	3.7%
9	3.7	100%	220	2.5%	1.7%	3.7%
10	4.8	100%	220	2.3%	2.0%	3.7%
11	5.9	100%	220	2.2%	1.6%	3.4%
12	6.9	100%	220	1.9%	1.5%	3.2%

VI. CONCLUSIONS

CASL's VERA was successfully used to predict the startup of TVA's new WBN2 reactor, and successfully benchmarked against the plant data obtained in the months during its power escalation to commercial operation. Reactivity predictions have been good, with a less than 10 ppmB (~100 pcm) difference from measurement for cases at zero power. Agreement in control bank and temperature reactivity worths was excellent, and the power distributions improved with power, so that recent agreement was within a 3.2% total RMS difference. Issues with power defect potentially due to fuel temperature models were identified and will be further investigated in the future.

Additionally, it was demonstrated that VERA can successfully complete an HPC simulation of more than 4,000 time steps, including more than 16,000 coupled iterations of 3-D pin-wise neutron transport and sub-channel

T/H with 100% successful convergence. The simulation, which required about 1 million core-hours, demonstrated that VERA can be brought to bear on realistic industrial problems and can be valuable for engineers in the commercial power industry.

NOMENCLATURE

GB = Gigabyte
pcm = percent milli-rho
ppmB = parts-per-million boron
RMS = root mean square (difference)

ACKNOWLEDGMENTS

The successful results generated in this application of VERA were enabled only through the collaboration of many members of the CASL team, including Kathleen Cunningham, formerly with TVA; Steven Halcomb and Christine Setter of TVA; Fausto Franceschini of Westinghouse; Shane Stimpson, Jess Gehin, and Ron Lee of ORNL; and the individual members of the software development teams who support MPACT, CTF, and Shift.

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