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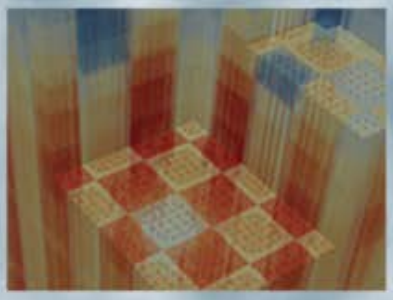
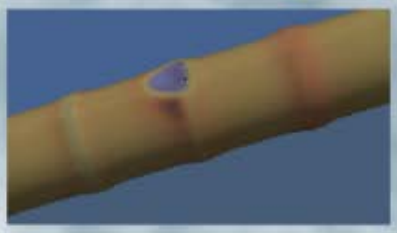
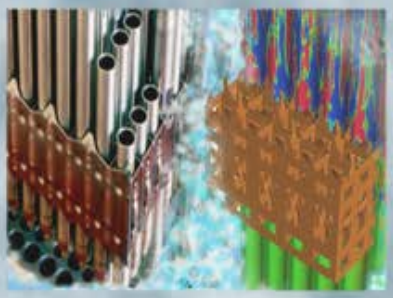
Analysis of the BEAVRS Benchmark using VERA-CS







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ANALYSIS OF THE BEAVRS BENCHMARK USING VERA-CS

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ABSTRACT

VERA-CS is the core simulator component of the Virtual Environment for Reactor Applications (VERA) which being developed by the Consortium for the Advanced Simulation of Light Water Reactors (CASL). VERA-CS is used to perform the Benchmark for Evaluation and Validation of Reactor Simulations (BEAVRS), which provides two cycles' worth of operating power history, along with a full, detailed description of the geometry, and measured data. Cycle 1 is simulated with VERA-CS and the results are compared to the measured zero power physics tests, critical boron concentration, and flux maps. Comparisons to the measured data show rod worth calculations within 5%, critical boron concentration within 50 ppm, and flux map 3D RMS values less than 4%.

Key Words: VERA-CS, MPACT, COBRA-TF, ORIGEN, BEAVRS, CASL

1 INTRODUCTION

The development of VERA-CS is a crucial component to being able to achieve the goals of CASL. VERA-CS needs to be able to accurately predict the detailed power, temperature, and isotopic distribution in the reactor throughout the lifetime of the fuel. This information becomes the basis to understand the underlying challenge problems that CASL is tasked to address. This work focuses on using VERA-CS to analyze the Benchmark for Evaluation and Validation of Reactor Simulations (BEAVRS) [1] for comparisons with measured plant data.

The BEAVRS Benchmark was released by MIT in 2013 to provide data from an operating nuclear reactor to the public to allow for validation of methods developments. This benchmark is similar to the data provided in the VERA Progression Benchmark [2]. The BEAVRS benchmark provides two cycles' worth of operational history, including power levels and boron concentrations. In addition, flux maps are provided at several points during each operating cycle. Figure 1 shows the power history for cycle 1, including indicators showing when flux maps and measured critical boron concentration measurements are made.

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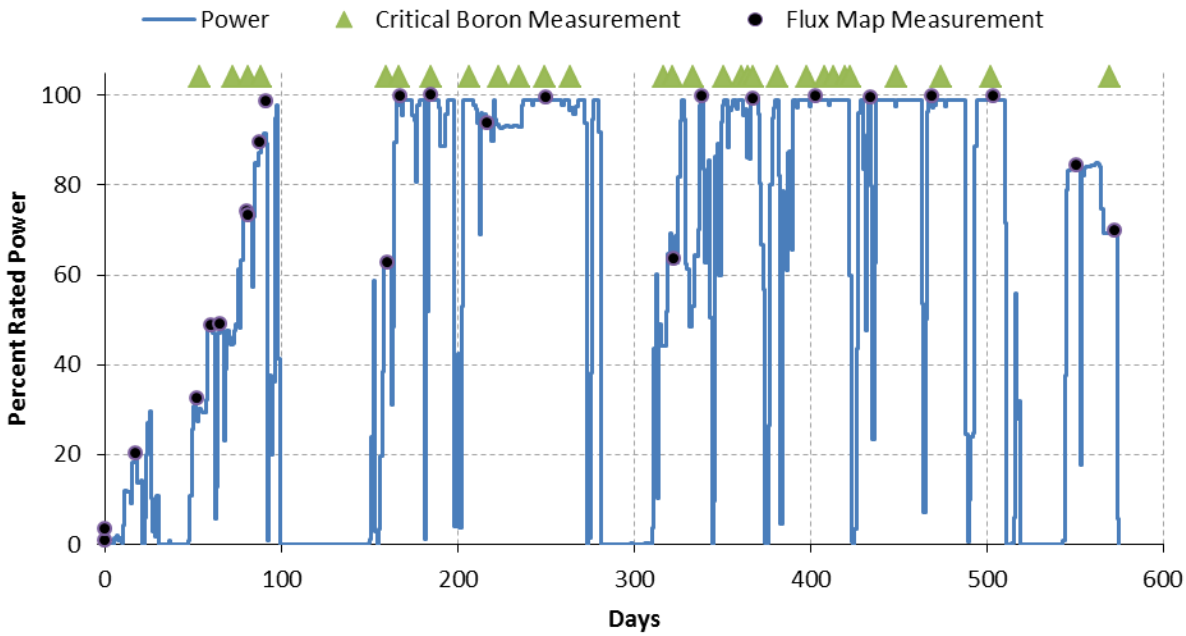

Figure 1. BEAVRS Cycle 1 Power History.

2 MODEL DESCRIPTION

As shown in Figure 1, the daily power history has considerable variation and would be very difficult to model explicitly with the methods of interest to CASL. Instead, the power history is simplified to reduce computational resources. The simplification is done in an attempt to preserve the general shape of the power history, capture the operating conditions of as many flux maps as possible, and preserve the total energy generation. By depleting using the flux map conditions, the neutron flux distribution can easily be compared throughout the entire operating cycle. The simplified power history for cycle 1 is shown in Figure 2.

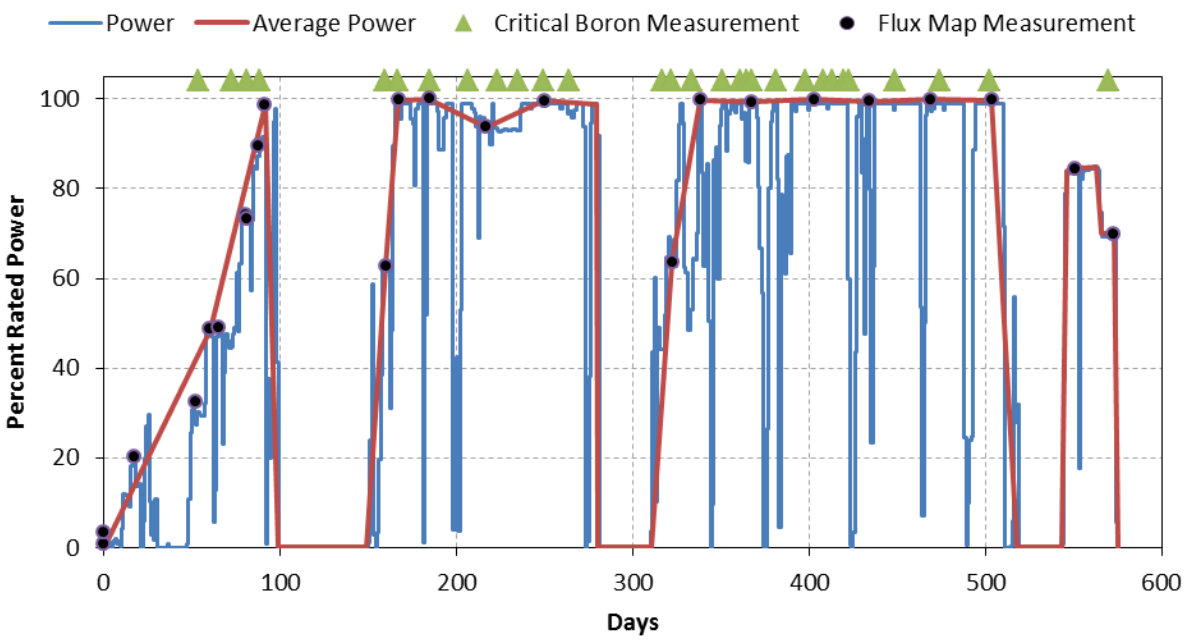

Figure 2. Simplified Cycle 1 Power History

The core geometry for cycles 1 and 2 is described in great detail in the benchmark specification. The model attempts to stay as faithful to the benchmark geometry as possible, but a few modifications are made in an attempt to make the model more realistic or to allow for geometric limitations of the code. The first approximation is to ignore the core barrel, neutron pads, downcomer, and reactor vessel because MPACT cannot currently model these regions explicitly. The MPACT model does explicitly model the baffle surrounding the core and approximately 20 cm of water outside of the baffle. The effect of this approximation was shown to be minimal for a similar reactor by [2]. Another approximation made in the core geometry is to ignore the effects of thermal expansion, creep, and swelling; VERA-CS models everything with cold dimensions.

A major difference between the model and the benchmark specification is the treatment of the axial reflector region. The benchmark specifies the upper and lower nozzle to be modelled with a considerable amount of stainless steel. The authors discerned that the benchmark is specifying up to 10 times the amount of steel that is in the nozzle and core plate region. Instead of using this amount of steel, a Westinghouse optimized fuel assembly (OFA) design found in reference [3] is used for the upper and lower reflector regions. This assembly design is consistent with the assemblies used in the operational reactor. In addition, a few changes were made after discussions with the benchmark organizers based on plans for future releases of the benchmark. These include; the addition of a hybrid control rod which has AIC tips and B_4C follower, modification to the spacer grid locations, and updates to the control rod all-in position. These modifications are expected in the next release of the benchmark specification.

With the exception of these differences, the model is built to the benchmark specification, including capturing the detail of the fuel, gap, clad in every fuel pin; explicit modelling of the PYREX burnable inserts (including detailed axial and radial description); explicit modeling of

the control rods (including end caps, plenums, and hybrid rod geometry); and explicit modelling of the instrument tubes to obtain accurate detector response.

3 METHODS

The VERA-CS core simulator has three main components; MPACT for reactor physics/neutron transport, COBRA-TF for thermal hydraulics, and ORIGEN for isotopics.

The 3D pin-resolved reactor transport code MPACT has been under development by Oak Ridge National Laboratory (ORNL) and the University of Michigan. The methods in MPACT have been documented in several places, [4, 5, 6] but a brief outline is presented here that discusses the 3D solution mechanism using the 2D/1D method and detector models. The 2D/1D method is used to solve the neutron flux distribution throughout the core. This is accomplished by using 2D method of characteristics (MOC) in the radial planes in order to capture the heterogeneity in the radial direction with high accuracy. Each pin cell is explicitly modelled, and even sub-pin detail can be captured. In the axial direction, a low-order transport solution is obtained through SP_3 on a pin-cell homogenized basis. The axial and radial solutions are linked through the use of transverse leakage terms which ensure neutron balance in every pin cell at convergence. More detail on the 2D/1D methodology used in MPACT can be found in reference [6]. MPACT uses a 47 energy group cross-section library based on ENDF/B VII data with subgroup parameters to capture self-shielding effects. MPACT has the ability to estimate the detector response during cycle operation for comparison with raw flux map data. This is obtained by explicitly modeling the instrument tubes in the geometry. Instead of placing a trace amount of U-235 into the instrument tube during the simulation, MPACT calculates the detector response during a post processing step. Once the flux solution is obtained, the local flux in each instrument tube is folded together with the U-235 cross section from the cross section library at the local temperature. This signal is obtained in every instrument tube and at every axial level in the model. The data are normalized and written to a binary output file for post-processing comparisons to the measured data.

COBRA-TF (CTF) [7] is a 9-equation subchannel code which is developed by ORNL and Penn State University. CTF solves for the mass, momentum, and energy field for liquid, vapor, and droplet phases in every subchannel in the core. CTF is directly coupled with MPACT to provide temperature and density feedback.

ORIGEN [8] is developed by ORNL and is well-known for its ability to accurately predict the change in nuclide concentration with time. ORIGEN is released through the SCALE [9] package but is directly integrated in MPACT through its API to calculate the change in nuclides for every depletable cross-section region (3 rings per pin, 49 axial levels, were used in the simulation of this benchmark).

4 RESULTS

As mentioned before, the BEAVRS benchmark provides data for two operational cycles (first and second cycle of operation) and includes measured boron concentrations and flux maps at several points in each cycle. Cycle 1 is the focus of the work here. This section is broken up

into two components. The first is the initial startup physics tests for cycle 1. The second section describes the comparisons to measured boron concentration and flux distribution during cycles 1.

4.1 Cycle 1 Zero Power Physics Tests

The cycle 1 zero power physics tests include five critical measurements with several different control rod configurations. Table 1 shows the calculated eigenvalues for all of the critical configurations with the specified boron concentration from the benchmark.

Table 1. BEAVRS Cycle 1 Zero Power Critical Configurations

	Eigenvalue	Difference [pcm]
ARO	0.99819	-181
D In	0.99972	-28
C/D In	0.99913	-87
A/B/C/D In	0.99769	-231
SE/SD/SC/A/B/C/D in	0.99660	-340

All five of the critical configurations show good agreement with the critical configuration and agree well with previously published solutions [10, 11]. When more control rod banks are inserted into the core, the solutions show larger differences than when only a few banks are inserted. Although, the agreement with previously published solutions is comparable, the significant modifications to the control rod description in the updated benchmark specification makes direction comparisons to other calculated results difficult.

In addition to the five critical conditions, the rod worth is measured for all banks. This was done by modelling the control rod in and out with constant boron. For control rods where critical boron concentrations were not given, the boron is interpolated based on the measured control rod worth. Table 2 shows the measured and predicted control rod worths. The predicted rod worth is less than 5% different for all banks.

Table 2. BEAVRS Cycle 1 Control Rod Worth

	Calculated	Measured	Difference
D	780	788	-1.1%
C with D In	1252	1203	4.1%
B with C/D In	1175	1171	0.3%
A with B/C/D In	568	548	3.6%
SC with A/B/C/D In	477	461	3.5%
SD with SC/A/B/C/D In	765	772	-1.0%
SE with SD/SC/A/B/C/D In	1071	1099	-2.5%

The other measurement that can be compared is the calculation of the isothermal temperature coefficient (ITC). The calculation of ITC was performed by performing a 5 degree Fahrenheit perturbation to all of the temperatures above and below nominal conditions. The ITC is calculated by using the eigenvalue of both of these points and is displayed in Table 2.

Table 3. BEAVRS cycle 1 ITC comparison

	Calculated ITC [pcm/°F]	Measured ITC [pcm/°F]
ARO	-2.09	-1.75
D In	-3.49	-2.75
C/D In	-8.30	-8.01

The ITC calculations all compare very well to the measured value even for different control rod configurations.

4.2 Cycle 1 Boron Letdown

In addition to the zero power measurements, VERA-CS is used to simulate the cycle 1 power history with the simplified model in Fig. 5. The calculated boron concentration throughout the cycle is shown in Fig. 5.

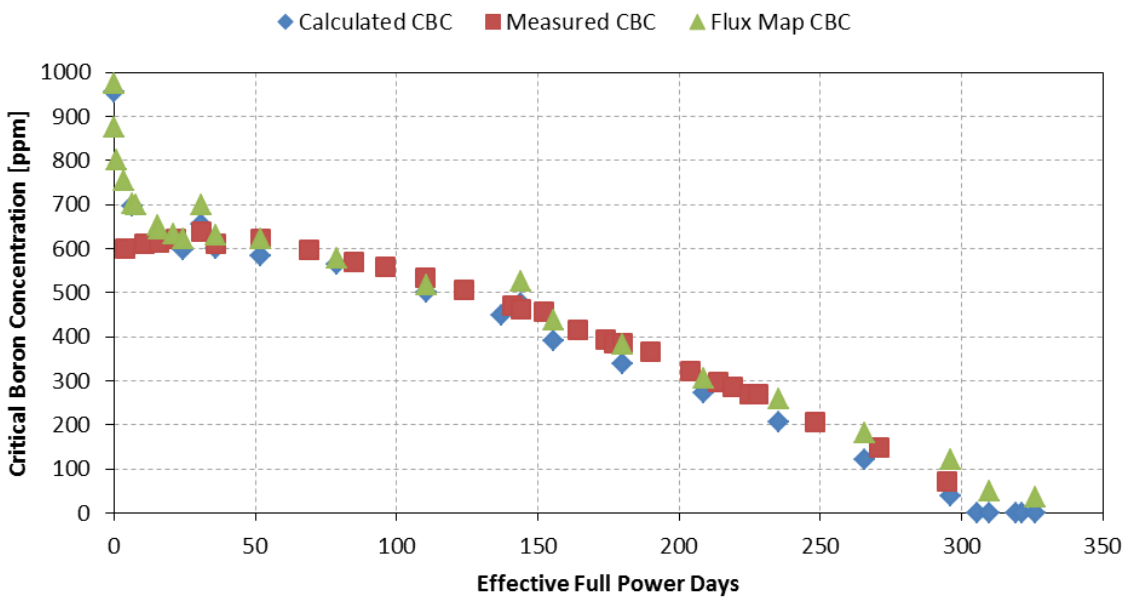

Figure 3. BEAVRS cycle 1 critical boron concentration (CBC)

Two different boron concentrations are reported in the specification. The first is the boron concentration corrected to 100% power and all rods out at regular intervals throughout the cycle. The second set is the instantaneous boron concentration at each flux map. Since the VERA-CS model depletes with all rods out, the results are more consistent with the corrected boron concentration although the boron concentrations at lower power levels should be expected to vary. The boron concentration agrees at the beginning of the cycle, but the difference grows as the cycle progresses. Figure 4 shows the difference from measured boron when the reactor is close to full power. The current cycle length is under predicted by 26 effective full power days (EFPDs).

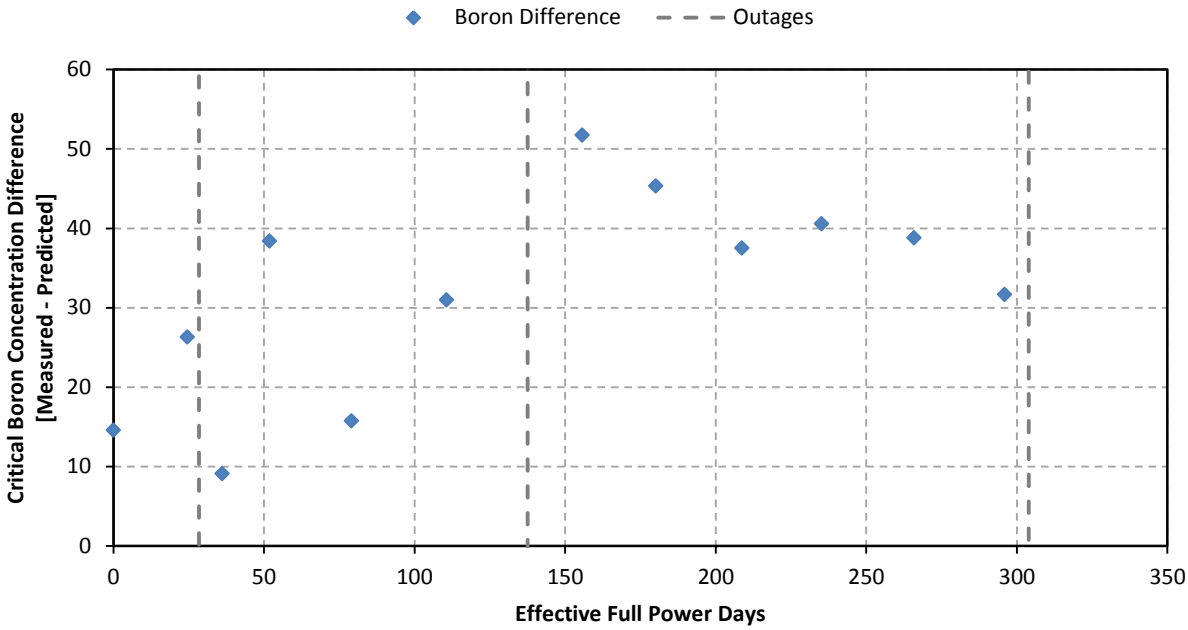

Figure 4: Comparison to Measured Boron Concentration

In addition to the critical boron concentration, 24 flux maps are provided at various points throughout cycle 1. 16 of these maps are chosen for comparison. The other 8 are excluded because they are all during the initial power ramp to full power and sufficient data is not provided in the benchmark to accurately model Xenon during this time frame. There are a few other flux maps that show larger discrepancies that are not at equilibrium conditions; during startup or shortly after a power maneuver, but the data is included in the analysis.

The detector responses are extracted using the detector model described above and normalized so it is consistent with the measured data[1]. Since the mesh in the model is different than the 61 level measured data, the predicted detector signal is fit with a cubic spline and integrated onto 61 evenly spaced regions. Each detector string is then compared against the detector data as shown in Figure 5.

Three metrics are used to determine the quality of the simulation for the flux maps. The first is the 3D root mean square (RMS) comparison. This is simply the RMS of the difference in detector response for all detector locations and every level.

$$RMS_{3D} = \sqrt{\frac{\sum_{\text{det}} \sum_{\text{N}_z} \left(\gamma_{\text{det},z}^{\text{meas}} - \gamma_{\text{det},z}^{\text{calc}} \right)^2}{N_{\text{det}} N_z}} \quad .$$

[1] Two modifications are made to the detector data. The zero power flux map is tilt corrected to minimize differences in symmetric locations at zero power. [12] Detector strings H-15 and G-09 for the 235 EFPD flux map are removed because of large spikes in the measured data:

The second is the 2D, or radial, RMS which is the difference of the axially integrated detector response:

$$RMS_{2D} = \sqrt{\frac{\sum_{\text{det}} \left(\sum_{\text{N}_z} \left(\gamma_{\text{det},z}^{\text{meas}} \right) - \sum_{\text{N}_z} \left(\gamma_{\text{det},z}^{\text{calc}} \right) \right)^2}{N_{\text{det}} N_z}} \ .$$

The last metric is the difference in axial offset as calculated by the detectors:

$$\Delta_{AO} = \frac{\sum_{\text{det}} \left(\frac{\sum_{z=N_z/2-1}^{\text{N}_z} \gamma_{\text{det},z}^{\text{meas}} - \sum_{z=1}^{\text{N}_z/2} \gamma_{\text{det},z}^{\text{meas}}}{\sum_{z=1}^{\text{N}_z} \gamma_{\text{det},z}^{\text{meas}}} - \frac{\sum_{z=N_z/2-1}^{\text{N}_z} \gamma_{\text{det},z}^{\text{calc}} - \sum_{z=1}^{\text{N}_z/2} \gamma_{\text{det},z}^{\text{calc}}}{\sum_{z=1}^{\text{N}_z} \gamma_{\text{det},z}^{\text{calc}}} \right)}{N_{\text{det}}} \ .$$

Flux maps throughout the cycle are compared and analyzed using the same methodology used for the zero power flux map. In each case, the 2D RMS, 3D RMS, and Difference in axial offset are recorded. Table 4 summarizes the comparisons for all of the flux maps above 90% power. The flux maps where it is questionable if the reactor has reached equilibrium after a power maneuver are highlighted in grey. Of the remaining flux maps, the radial RMS is between 1 and 2% and the 3D RMS is between 3 and 5%. In most cases, the comparison of axial offset is also less than 0.5%.

EFPD	Power	Boron	2D RMS	3D RMS	A/O Difference
0.0	0.0	975	1.79%	3.75%	1.70%
24.5	98.7	623	2.73%	4.07%	0.07%
36.1	99.8	630	1.84%	3.49%	0.22%
51.9	100.0	621	1.68%	2.98%	-0.07%
79.1	93.8	578	1.78%	3.60%	-1.76%
110.6	99.6	517	1.54%	3.29%	1.07%
155.7	99.7	437	1.27%	3.36%	-1.35%
180.1	99.3	383	1.26%	3.71%	-0.73%
208.7	99.9	306	1.37%	2.81%	-0.17%
235.1	99.5	259	2.09%	3.74%	1.15%
265.8	99.9	180	1.28%	5.05%	2.85%
296.0	99.8	120	1.19%	4.94%	3.31%

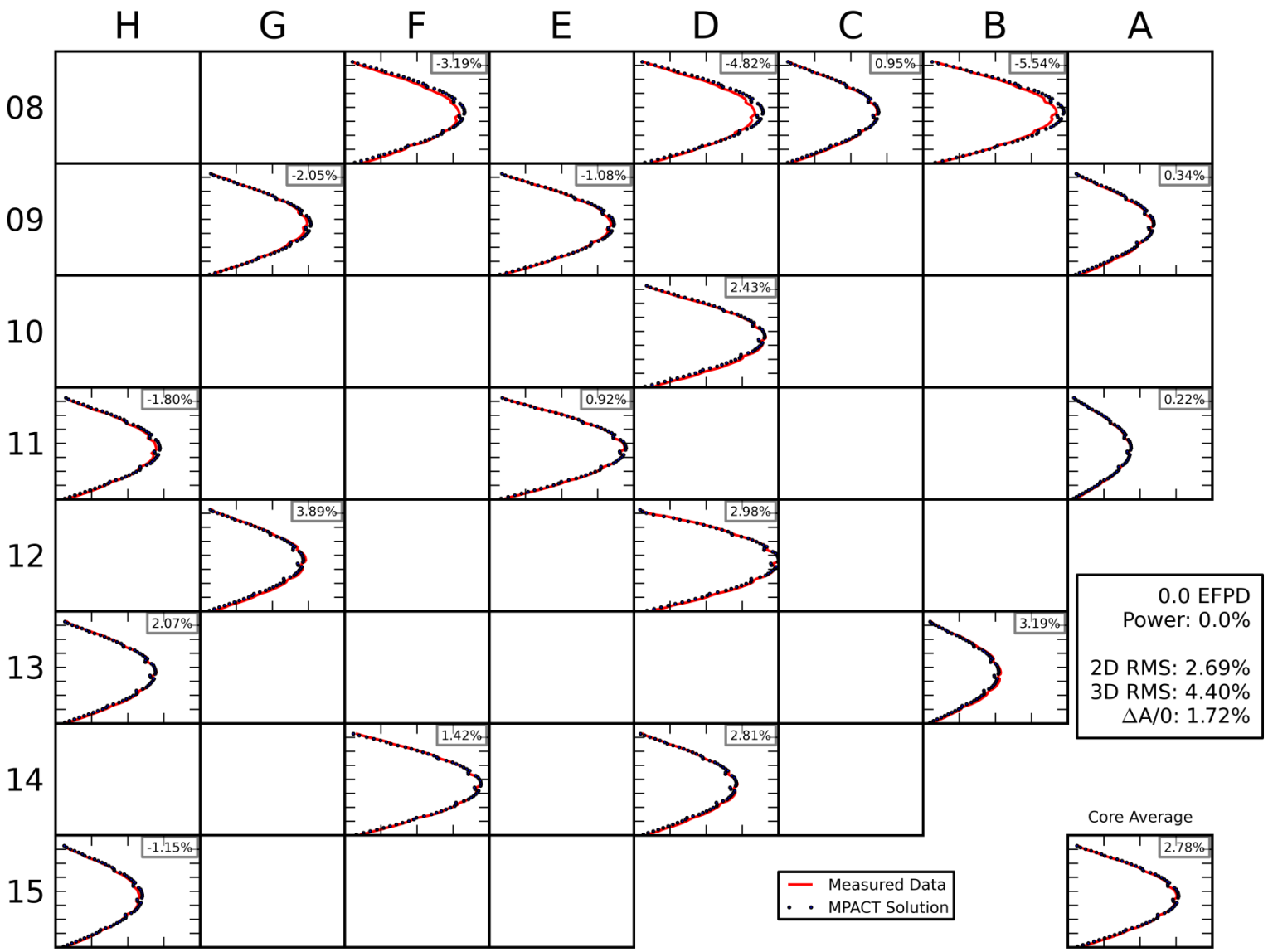

Figure 5: BEAVRS Cycle 1 BOC Flux Map Comparison

5 CONCLUSIONS

VERA-CS was used to simulate cycle 1 of the BEAVRS benchmark using simplified power histories based on a detailed daily power history. Several comparisons were made to the measured cycle data, including the analysis of hot zero power physics tests for critical conditions, control rod worths, and ITC. A zero power flux map comparison shows reasonable results, and a 2D RMS error of 2.7% is reported. The simulation of cycle 1 shows good comparisons of critical boron concentration throughout the operating history. In addition, the flux map comparisons show a consistent comparison throughout the cycle. Future work will focus on further improvements to increase the accuracy of the simulation and also extend to cycle 2.

6 ACKNOWLEDGMENTS

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