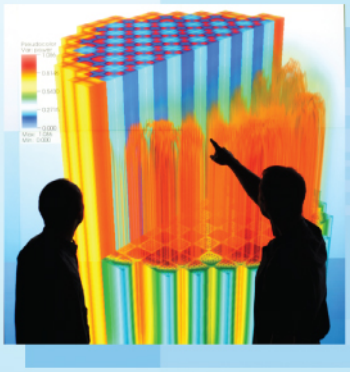
CASL-U-2014-0045-000

Power uprates
and plant life extension



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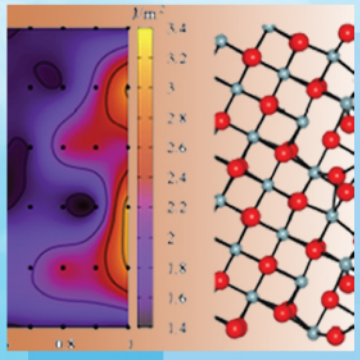

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Consortium for Advanced Simulation of LWRs

MPACT Testing and Benchmarking Results

March 31, 2014

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U.S. DEPARTMENT OF ENERGY | Nuclear Energy

REVISION LOG

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EXECUTIVE SUMMARY

This document provides detailed reactivity and fission rate distribution results for MPACT for the Core Physics Benchmark Progression Problems 1-5, including comparisons to initial startup data from Watts Bar Nuclear Unit 1. Also included are computer requirements and runtimes for each type of problem and feedback for issues encountered during the testing.

Testing for the benchmark problems that do not require thermal-hydraulic feedback has been very successful. Testing for the coupled problems (6 and 7) is still ongoing and will be documented in a future revision or separate document.

A few issues have been identified needing more research/investigation before all of these problems have ideal solutions. These items are included in the Section 8 near the end of this document.

MPACT has successfully solved all of the zero power core physics progression problems. The computer resources required and runtimes were all acceptable, though faster cases would be preferable considering there was no thermal-hydraulic feedback. MPACT converged very reliably for all 3D problems, expect in a few isolated studies where very thin axial planes were purposely created to attempt to quantify the errors in the control rod tip homogenization model. Despite the issues listed in Section 8, the accuracy of MPACT compared to the reference solution is considered to be very good.

Table 1: MPACT Performance Summary

Problem	Typical Eigenvalue Difference (pcm)	Typical Pin Power RMS (%)	Number Compute Cores	Typical Runtime
1	-211	--	8	~3 secs
2	-126	0.12%	8	~1 mins
3	-116	0.27%	464	~2 mins
4	-113	0.95%	464	~33 mins
5	-88	0.74%	2784	~75 mins
4-2D	-67	0.13%	72	~2 mins
5-2D	-50	0.65%	448	~21 mins

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ACRONYMS

2D	Two-Dimensional
3D	Three-Dimensional
AIC	Silver-Indium-Cadmium control rods
ARI	All Rods In
ARO	All Rods Out
B_4C	Boron Carbide control rods
BOC	Beginning-of-Cycle
BOL	Beginning-of-Life
DBW	Differential Boron Reactivity Worth
HFP	Hot Full Power
HZP	Hot Zero Power
ITC	Isothermal Temperature Reactivity Coefficient
IFBA	Integral Fuel Burnable Absorber (here WEC's ZrB_2)
LWR	Light Water Reactor
MOC	Method of Characteristics
MPACT	Michigan PArallel Charactistic based Transport Computer Code
OLCF	Oak Ridge Leadership Computing Facility
ORNL	Oak Ridge National Laboratory
PCM	Percent milli (10^{-5})
PHI	Physics Integration Focus Area
PWR	Pressurized Water Reactor
RCCA	Rod Cluster Control Assembly
RMS	Root Mean Square
RTM	Radiation Transport Focus Area
TVA	Tennessee Valley Authority
UM	University of Michigan
WABA	Wet Annular Burnable Absorber
WBN1	Watts Bar Nuclear Unit 1
ZPPT	Zero Power Physics Tests

INTRODUCTION

The Michigan PArallel Charactistics-based Transport (MPACT) (Ref. 1) code has been thoroughly tested for the Core Physics Benchmark Progression Problems 1-5 (Ref. 2), including comparison against continuous energy Monte Carlo reference solutions from KENO-VI and against measured data from the initial startup testing of Tennessee Valley Authority's (TVA) Watts Bar Nuclear Unit 1 (WBN1) commercial power plant. This document provides detailed results for each problem, including comparisons of reactivity, fission rate distributions (herein referred to as 'pin power'), and control rod reactivity worths. Computational requirements and user feedback are also included.

Details about MPACT and the model/methods it employs can be found in References 1 and 3 and many other CASL documents. The following characteristics were used for all problems when performing the testing:

- The standard VERAIn input for geometry was used for each problem. This is consistent with what has been used for both Insilico (Ref. 3) and Shift as well.ρ
- Typical MOC parameters:
  - 0.05 cm ray spacing (0.005 for IFBA)
  - 16 azimuthal angles per octant
  - 2 polar angles per octant
  - Chebyshev-Yamamoto quadrature set
- Standard or better meshing for fresh fuel
  - 8 azimuthal flat source regions per pin cell
  - 3 radial rings per fuel rod and guide/instrument tube
- Typical tolerances (where not specified as other):
  - 1e-6 on flux
  - 1e-6 on eigenvalue
- P2 scattering treatment
- NEM nodal method for the 2D/1D axial solution (Ref. 1)
- CMFD for acceleration and stability
- 56 group ORNL sub-group ENDF/B-VII.0 cross section library: **declib56g_e7_09042013_p0mixed.fmt**
- All cases were executed on the EOS supercomputer at the Oak Ridge Leadership Computing Facility (OLCF). EOS is a 744 node Cray cluster with 11,904 processors and 47.6 TB of memory.
- Comparisons to reference solutions were made per the following:
  - Reactivity difference in pcm: $(k_{MPACT} - k_{REF})\times 10^5$
  - Pin power (normalized fission rate) difference in %: $(P_{MPACT} - P_{REF})\times 100$
  - Pin power performace summarized as ***RMS*** (root mean square difference) and ***MAX*** (maximum absolute difference).
  - Control rod worths in Δρ pcm: $(1/k_1 - 1/k_2)\times 10^5$

The specification and details regarding the reference solutions are available in Reference 2.

1. PROBLEM 1 – 2D PIN CELL

Table 1-1 contains the eigenvalue results for the single pin problems. Each case was run with 8 processors on a single EOS compute node.

Table 1-1: Problem 1 MPACT Results

Case	Description	Reference (± 8 pcm)	MPACT Difference (pcm)	Run Time (secs)
1A	565 K	1.187038	**-137**	2.3
1B	600 K	1.182149	**-194**	2.4
1C	900 K	1.171722	**-294**	2.3
1D	1200K	1.162603	**-369**	2.3
1E	IFBA – 600K	0.771691	**-61**	11.3
Average			**-211**	

A small but clear bias exists with increasing fuel temperature. This will be further evaluated with Problem 2. The IFBA pin results (1E) looks very good, but a 10x decrease in the MOC ray spacing was required, which resulted in a 5x increase in runtime.

2. PROBLEM 2 – 2D LATTICE

Table 2-1 contains the eigenvalue and fission rate distributions results for the 2D lattice cases. Each case was run with 8 processors on a single EOS compute node.

Table 2-1: Problem 2 MPACT Results

Case	Description	Reference (± 3 pcm)	k-eff (pcm)	RMS (%)	Max (%)	Run Time (secs)
2A	565 K	1.182175	**-69**	**0.10%**	**0.17%**	48
2B	600 K	1.183360	**-116**	**0.07%**	**0.15%**	48
2C	900 K	1.173751	**-193**	**0.07%**	**0.13%**	48
2D	1200 K	1.165591	**-278**	**0.06%**	**0.12%**	48
2E	12 Pyrex	1.069627	**-72**	**0.10%**	**0.21%**	49
2F	24 Pyrex	0.976018	**-64**	**0.13%**	**0.26%**	54
2G	24 AIC	0.847695	**-287**	**0.16%**	**0.31%**	54
2H	24 B_4C	0.788221	**-60**	**0.22%**	**0.47%**	54
2I	Instrument Thimble	1.179916	**-68**	**0.07%**	**0.16%**	48
2J	Instr. + 24 Pyrex	0.975193	**-56**	**0.12%**	**0.21%**	54
2K	Zoned + 24 Pyrex	1.020063	**-59**	**0.13%**	**0.24%**	54
2L	80 IFBA	1.018915	**-66**	**0.07%**	**0.18%**	255
2M	128 IFBA	0.938796	**-56**	**0.07%**	**0.14%**	262
2N	104 IFBA + 20 WABA	0.869615	**-110**	**0.12%**	**0.24%**	296
2O	12 Gadolinia	1.047729	**-113**	**0.10%**	**0.28%**	46
2P	24 Gadolinia	0.927410	**-238**	**0.13%**	**0.31%**	49
2Q	Zirc4 Spacer Grid	1.171940	**-243**	**0.27%**	**0.86%**	48
Average			**-126**	**0.12%**	**0.26%**	

The temperature bias observed for Problem 1 is also apparent for Problem 2. The IFBA lattice results (2L-2N) look very good, but a 10x decrease in the MOC ray spacing was required, which like the single pin cell cases, resulted in a 5x increase in runtime.

A reactivity bias of about -200 pcm is also evident for AIC controlled lattices.

A reactivity bias of about -180 pcm and nearly 1% in peak pin power exists for the spacer grid case. The distribution shown in Figure 2-3 seems to indicate an inconsistency between the way the grid material is modeled in MPACT verses the reference solution.

Pin power distribution comparisons for cases 2H, 2P, and 2Q are provided below, using octant symmetry.

-0.31%	-0.23%							
0.06%	-0.09%	-0.07%						
	0.19%	0.15%						
0.21%	-0.05%	0.01%	0.29%	0.17%				
0.22%	-0.05%	0.04%	0.41%	0.36%				
	0.31%	0.21%		0.32%	0.29%	-0.05%		
0.21%	-0.02%	-0.12%	0.18%	-0.07%	-0.05%	-0.24%	-0.26%	
-0.14%	-0.21%	-0.26%	-0.20%	-0.25%	-0.24%	-0.25%	-0.32%	-0.47%

Max: 0.41% Min: -0.47% Avg: 0.22%

Figure 2-1: Problem 2H (AIC) Power Distribution Comparison

-0.24%	-0.10%							
-0.12%	0.09%	0.01%						
	-0.25%	-0.08%						
0.10%	0.03%	-0.06%	-0.05%	-0.01%				
-0.02%	0.24%	0.03%	-0.31%	-0.14%				
	-0.12%	-0.20%		-0.10%	0.00%	0.00%		
-0.11%	0.08%	0.21%	0.01%	0.15%	0.02%	0.23%	0.10%	
-0.07%	0.02%	-0.02%	0.22%	0.01%	0.04%	0.11%	0.06%	0.04%

Max: 0.24% Min: -0.31% Avg: 0.13%

Figure 2-2: Problem 2P (Gadolinia) Power Distribution Comparison

0.36%	0.34%							
0.34%	0.30%	0.28%						
	0.30%	0.27%						
0.29%	0.26%	0.24%	0.28%	0.25%				
0.22%	0.17%	0.21%	0.22%	0.14%				
	0.11%	0.08%		0.06%	-0.01%	-0.09%		
-0.03%	0.02%	0.04%	-0.05%	-0.05%	-0.15%	-0.24%	-0.29%	
-0.27%	-0.20%	-0.24%	-0.30%	-0.29%	-0.36%	-0.48%	-0.60%	-0.86%

Max: 0.36% Min: -0.86% Avg: 0.27%

Figure 2-3: Problem 2Q (Grid) Power Distribution Comparison

3. PROBLEM 3 – 3D HZP ASSEMBLY

Table 3-1 contains the eigenvalue and fission rate distributions results for the 3D assembly cases. Each case was run with 464 processors on 15 compute nodes, utilizing less than 2 GB of memory per core.

Table 3-1: Problem 3 MPACT Results

Case	Description	Reference (± 0.6 pcm)	k-eff (pcm)	RMS (%)	Max (%)	Run Time (secs)
3A	600 K – No Poisons	1.175722	**-109**	**0.21%**	**0.89%**	116
3B	565 K – 16 Pyrex	1.000154	**-122**	**0.34%**	**1.35%**	124
Average			**-116**	**0.27%**	**1.12%**	120

Figure 3-1 displays the comparisons in the axial power shapes for each case. There is a small bias (< +0.5%) evident at the axial locations of spacer grids. This bias is also inconsistent in direction from the lattice case 2Q. No axial tilt bias is observable. Figure 3-2 provides the radial comparisons, which are very good.

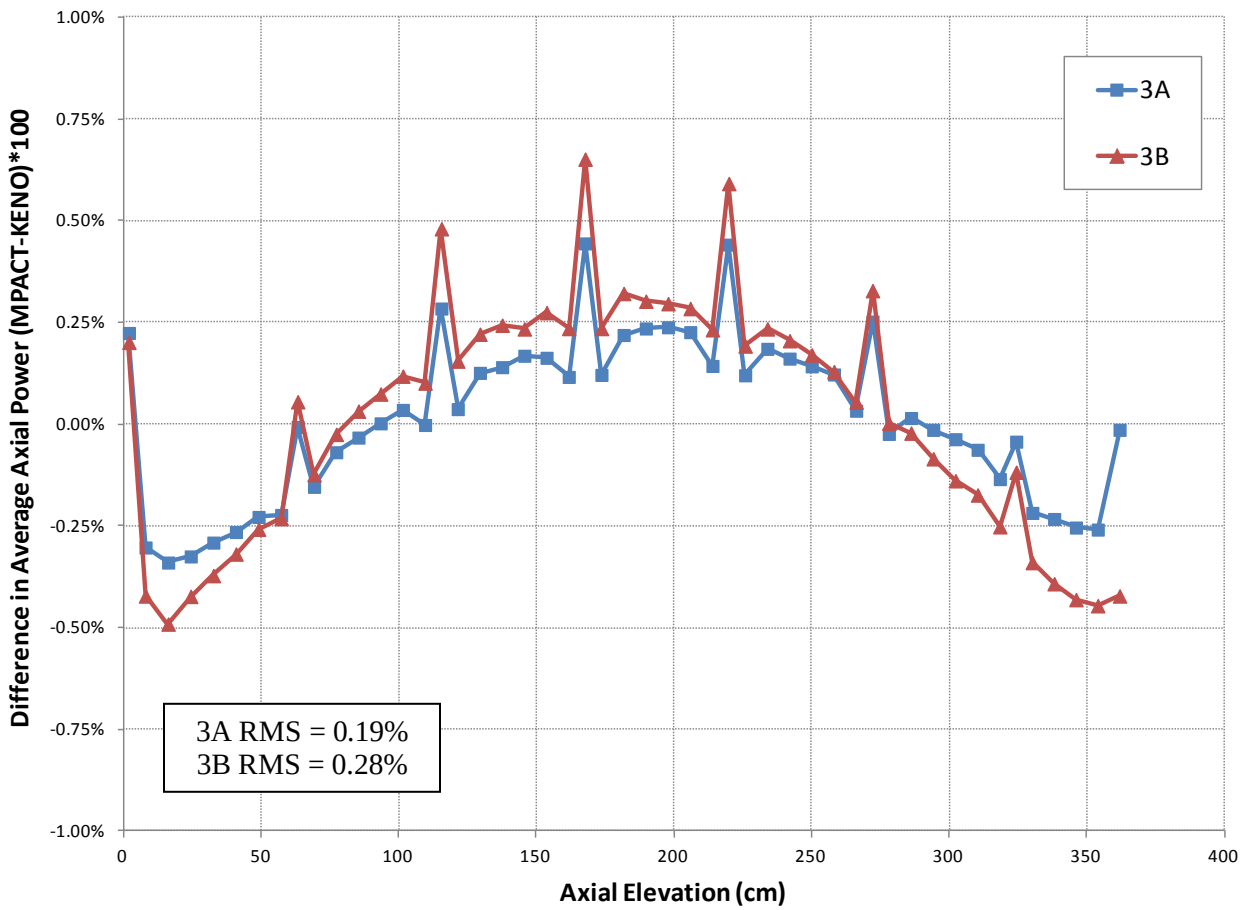

Figure 3-1: Problem 3 Axial Power Shape Differences

3A

0.01%	0.10%							
-0.03%	0.11%	0.10%						
	-0.04%	-0.08%						
-0.06%	0.07%	0.04%	-0.08%	0.05%				
-0.08%	0.05%	0.07%	-0.09%	-0.10%				
	-0.08%	-0.10%		-0.08%	-0.09%	0.05%		
-0.08%	0.07%	0.06%	-0.05%	0.05%	0.02%	0.03%	0.06%	
0.00%	0.05%	0.03%	0.00%	0.02%	0.04%	0.03%	0.01%	-0.04%

Max: 0.11% Min: -0.10% RMS: 0.06%

3B

-0.12%	-0.02%							
0.23%	0.04%	-0.04%						
	0.22%	-0.20%						
0.20%	0.00%	-0.07%	-0.17%	0.02%				
-0.21%	-0.08%	0.02%	0.27%	0.30%				
	-0.21%	0.18%		0.33%	0.30%	0.05%		
-0.32%	-0.10%	0.00%	0.25%	0.04%	0.01%	-0.06%	-0.08%	
-0.21%	-0.15%	-0.10%	-0.06%	-0.08%	-0.09%	-0.10%	-0.15%	-0.22%

Max: 0.33% Min: -0.32% RMS: 0.17%

Figure 3-2: Problem 3 Radial Power Shape Comparisons

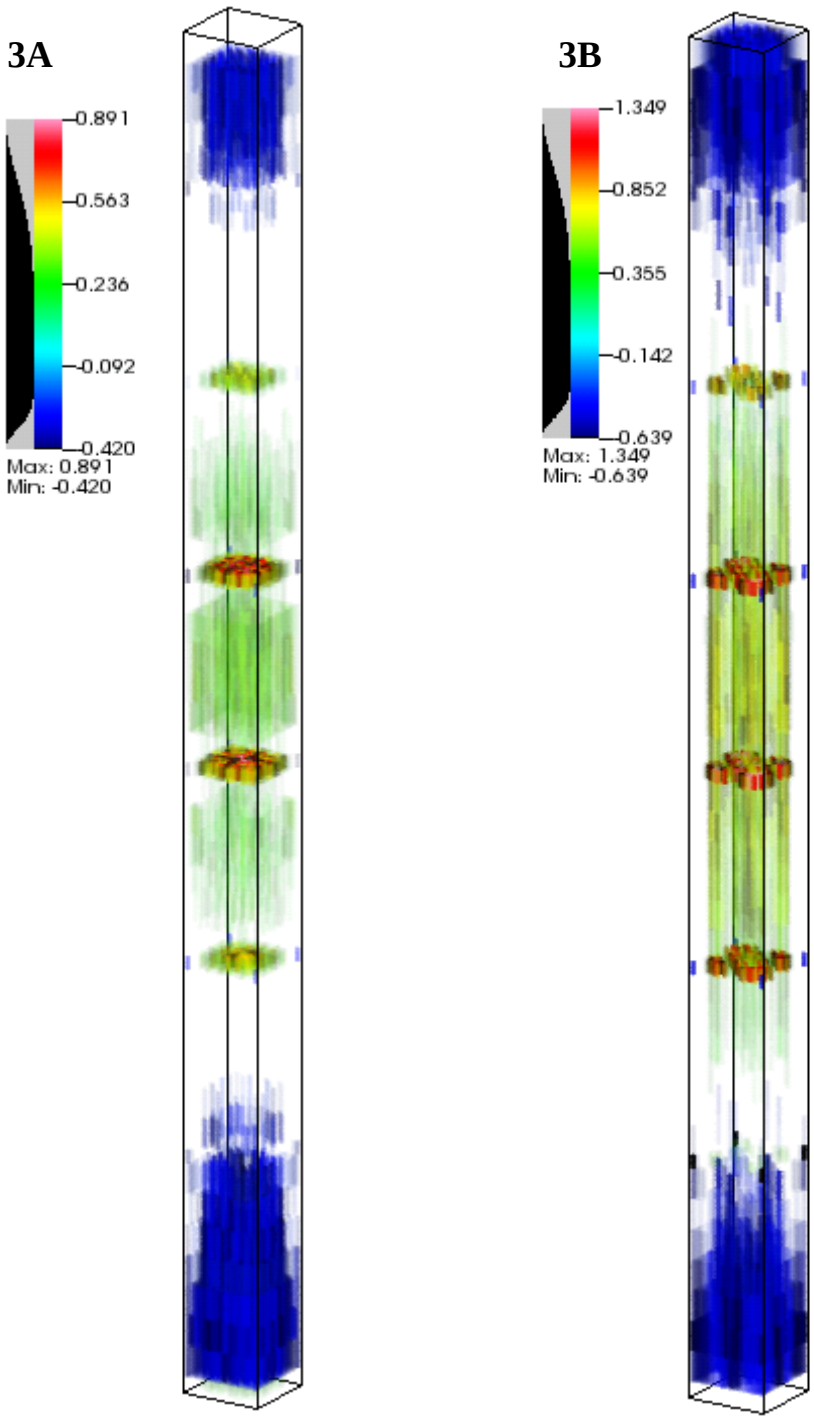

Figure 3-3: Problem 3 3D Power Distribution Comparisons

4. PROBLEM 4 – 3D 3X3 ASSEMBLIES WITH CONTROL ROD

Table 4-1 contains the eigenvalue and fission rate distributions results for all the Problem 4 cases. Each case was run with 4176 processors on 131 compute nodes, utilizing less than 2 GB of memory per core.

Table 4-1: Problem 4 MPACT Results

Rod Position	RCCA % Withdrawn	Reference (± 2 pcm)	k-eff (pcm)	RMS (%)	Max (%)	Run Time (mins)
257.9 cm	--	0.998981	**-102**	**0.95%**	**1.98%**	3.3
0 steps	0%	0.972411	**-106**	--	--	3.7
23 steps	10%	0.973679	**-113**	--	--	4.0
46 steps	20%	0.979363	**-153**	--	--	4.5
69 steps	30%	0.987043	**-153**	--	--	3.9
92 steps	40%	0.992341	**-130**	--	--	3.7
115 steps	50%	0.995745	**-115**	--	--	3.5
138 steps	60%	0.998028	**-108**	--	--	3.5
161 steps	70%	0.999551	**-101**	--	--	3.6
184 steps	80%	1.000584	**-96**	--	--	3.1
207 steps	90%	1.001168	**-89**	--	--	3.0
230 steps	100%	1.001385	**-93**	--	--	3.0
Average			**-113**			3.6

Note that the reference solutions for the integral rod worth cases have much higher power distribution uncertainties and were not used here for comparison.

Additionally, some cases were run on 464 cores for 32.7 minutes without radial decomposition.

The initial MPACT results for Problem 4 indicated problems when the RCCA poison tip does not lie on an axial mesh boundary. The worst case was the 20% withdrawn case, which resulted in a **-239** pcm reactivity error (and **49%** pin power error compared to the KENO reference). To attempt to eliminate this error, each case was rerun with either an additional axial plane at the tip boundary, or a modified axial mesh that placed the tip on a mesh boundary (but no longer matched the reference solutions). The following table provides the error calculated to be related to the control rod tip model for each case.

Table 4-2: Problem 4 Error Due To RCCA Tip Homogenization

Rod Position	RCCA % Withdrawn	Height of Plane with Tip (cm)	Control Fraction	k-eff Error (pcm)
0 steps	0%	8.211	85.2%	**-1**
23 steps	10%	8.211	40.5%	**20**
46 steps	20%	8.065	39.4%	**86**
69 steps	30%	3.81	71.8%	**12**
92 steps	40%	8.065	81.2%	**13**
115 steps	50%	8.065	75.7%	**17**
138 steps	60%	8.065	70.2%	**14**
161 steps	70%	8.065	17.5%	**18**
184 steps	80%	8.065	12.0%	**11**
207 steps	90%	7.9212	4.8%	**4**
230 steps	100%	--	--	--

The reference solutions for the rod worth cases have an average pin power uncertainty of 0.24%, with a maximum uncertainty of nearly 4%. Initial comparison of MPACT's power distribution for these cases resulted in quite large errors, mostly due to the control rod tip homogenization. 70% of the cases had peak pin power differences of nearly 10% or greater, up to 24% and 49% differences.

Based on the manually modified results to align the control rod tip with a mesh boundary, the MPACT integrated rod worth curve is shown in Figure 4-1 and compared to the reference solution. The integral worth comparison is excellent with only a **0.6%** total error. Figure 4-2 provides the corresponding differential rod worths.

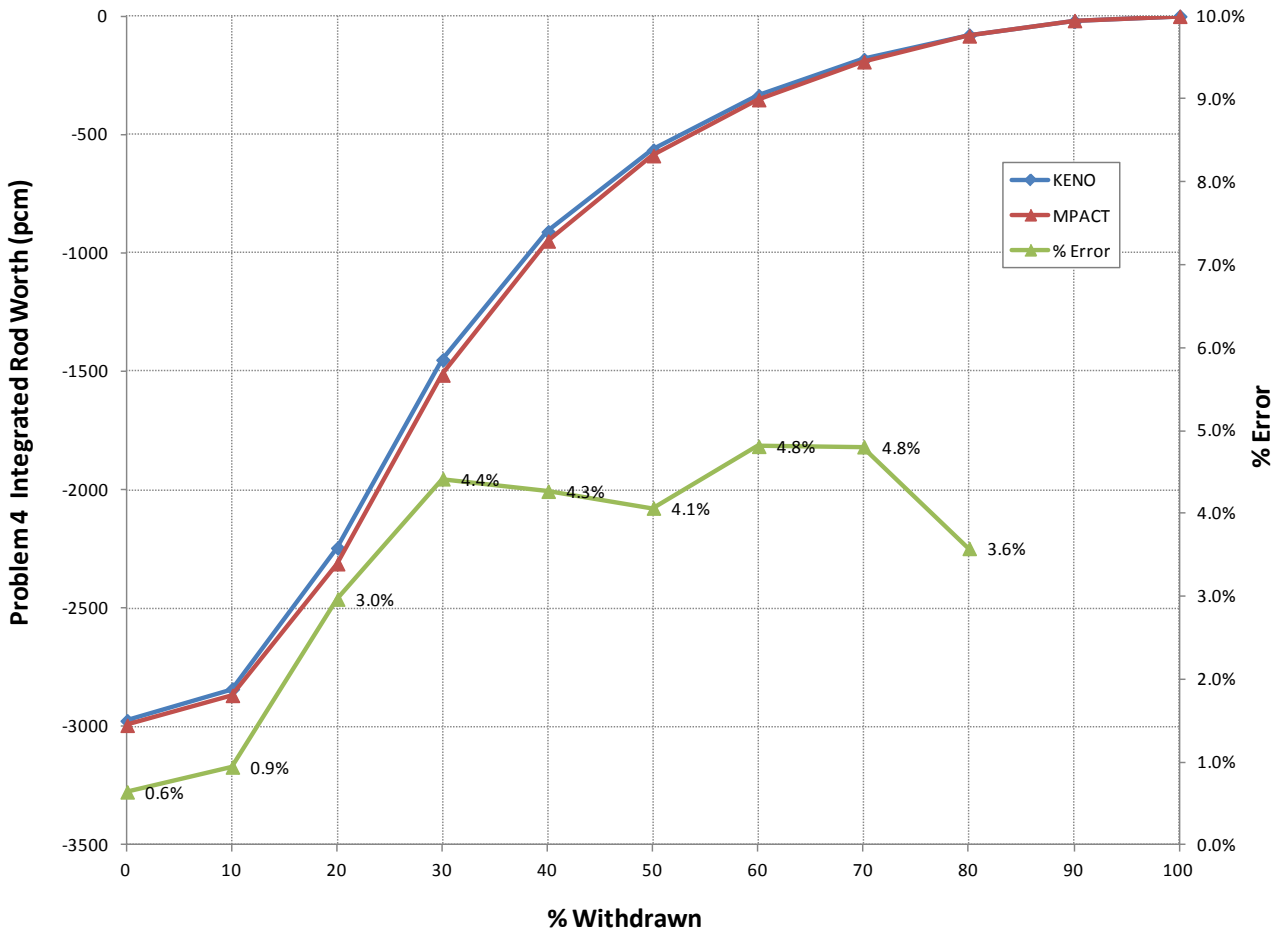

Figure 4-1: Problem 4 Integral Rod Worth Comparison

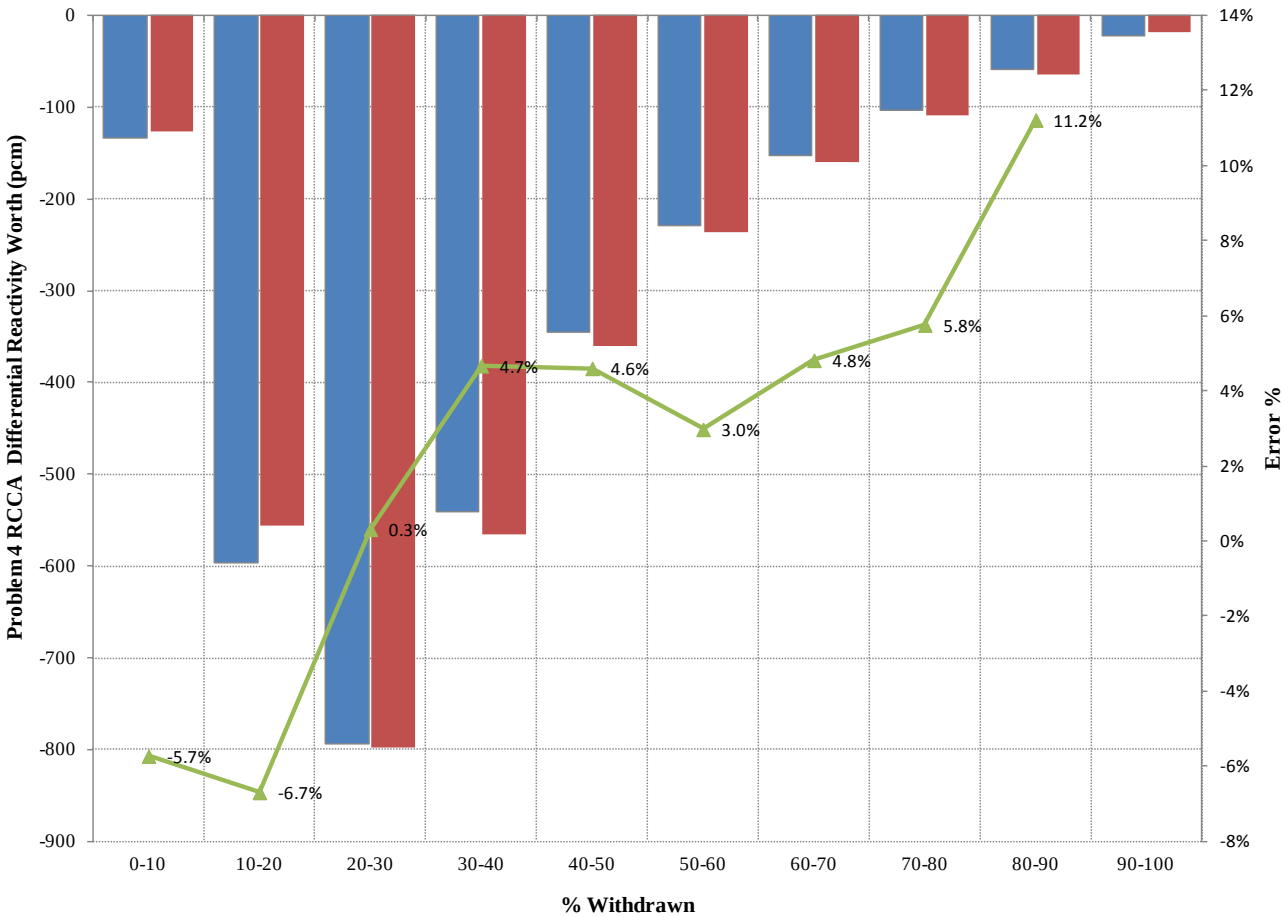

Figure 4-2: Problem 4 Differential Rod Worth Comparison

Figure 4-3 displays the comparisons in the axial power shapes for each assembly and the problem average. In addition to the same type of bias observed for the spacer grids in Problem 3, there is also a clear axial tilt in the power, up to approximately 1.5%, resulting in an axial offset difference of approximately 1%. The shape of the axial tilt is consistent with the reactivity bias observed with the AIC controlled lattice. There is also a bias of approximately 0.5% in the lowest axial plane containing the control rod in the center assembly.

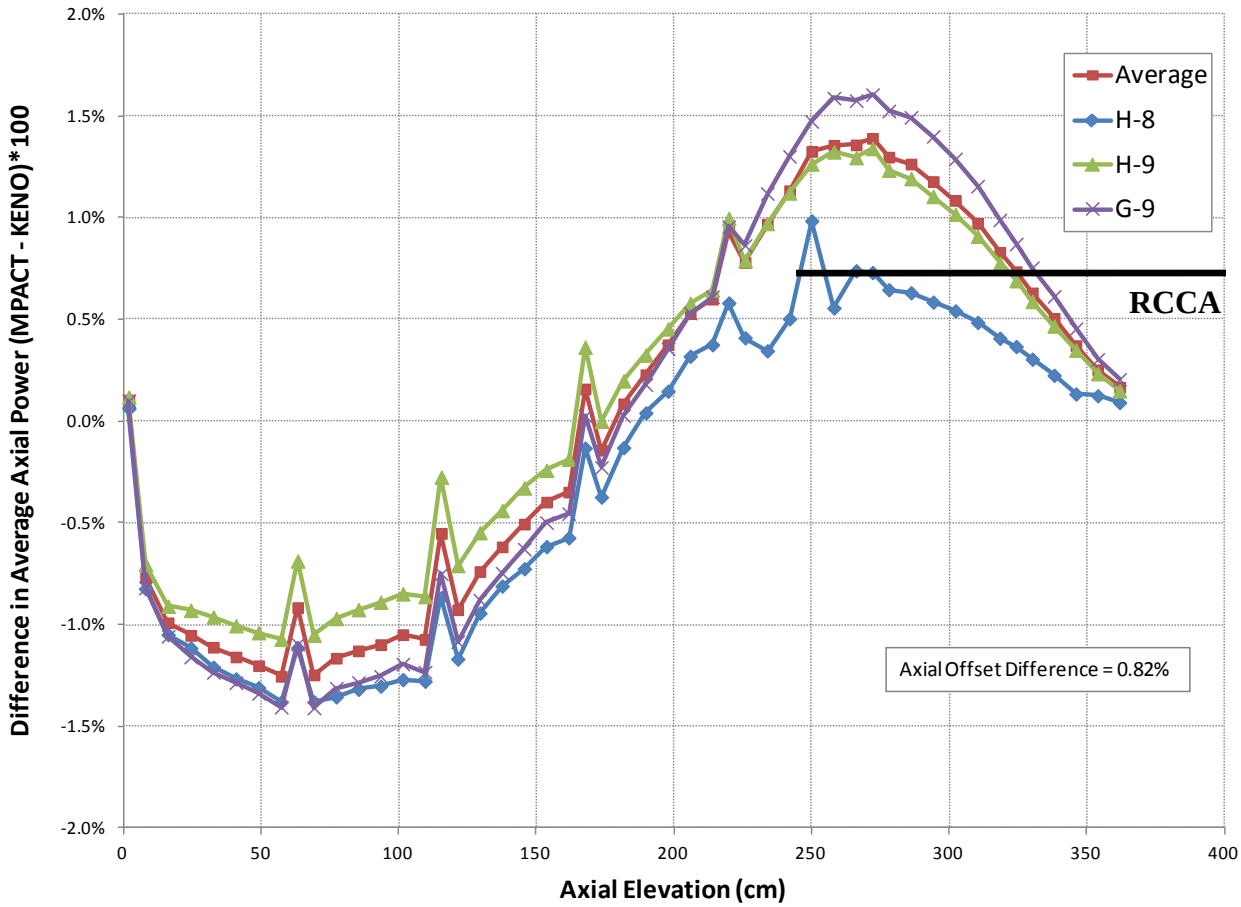

Figure 4-3: Problem 4 Axial Power Shape Comparisons by Assembly

Unlike the axial shape issues, the radial power distribution agrees very well with the reference solution with a radial pin power RMS of **0.17%** and peak pin error of **0.45%.** The largest difference in integrated assembly power is only **0.29%**. This distribution is provided in Figure 4-4 below.

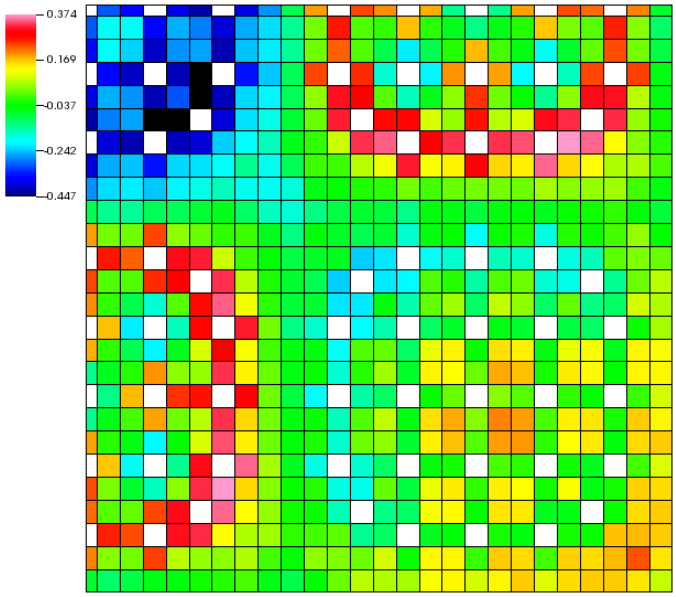

Figure 4-4: Problem 4 Radial Power Shape Comparison

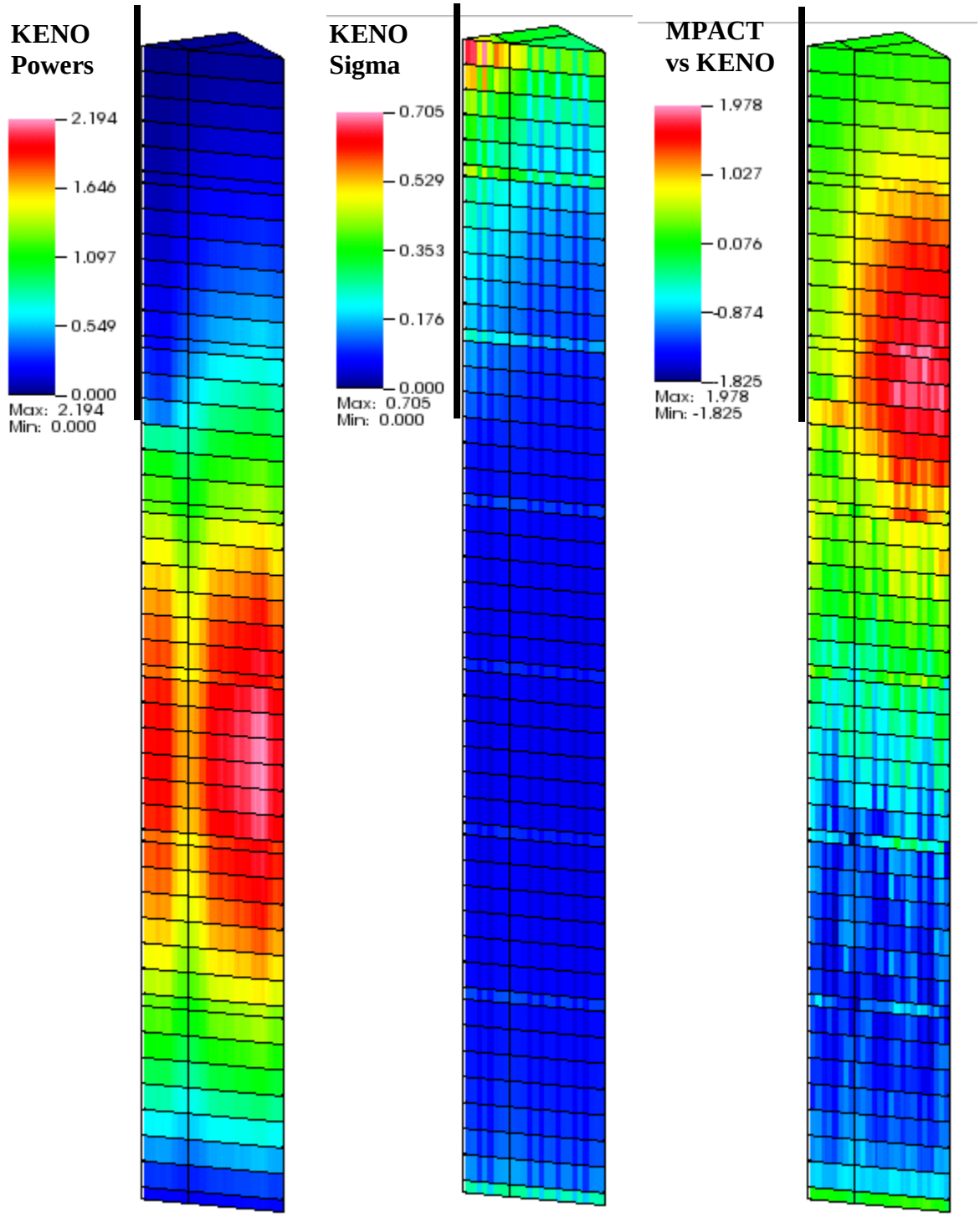

Figure 4-5: Problem 4 3D Power Shape Comparison
(slice through 45 degress)

5. PROBLEM 5 – WBN1 ZERO POWER PHYSICS TESTS

Table 5-1 contains the eigenvalue results for all the Problem 5 cases. Each case was run with 2784 processors on 174 compute nodes, utilizing up to 4 GB of memory per core. The cases took between 1.1 and 1.5 hours each and utilized increased MOC ray spacing (0.1 cm) and looser convergence criteria (flux=1e-4 and k=1e-5).

Table 5-1: Problem 5 MPACT Eigenvalue Results

			Bank Position (steps withdrawn)									
Case	**Boron (ppm)**	**Temp (K)**	**A**	**B**	**C**	**D**	**SA**	**SB**	**SC**	**SD**	**Reference (< 2 pcm)**	**k-eff diff (pcm)**
1	1285	565	-	-	-	167	-	-	-	-	0.999899	**-77**
2	1291	↓	-	-	-	-	-	-	-	-	1.000321	**-73**
3	1170	↓	0	-	-	97	-	-	-	-	0.998797	**-97**
4	↓	↓	-	0	-	113	-	-	-	-	0.999358	**-106**
5	↓	↓	-	-	0	119	-	-	-	-	0.999039	**-102**
6	↓	↓	-	-	-	18	-	-	-	-	0.999084	**-85**
7	↓	↓	-	-	-	69	0	-	-	-	0.999022	**-112**
8	↓	↓	-	-	-	134	-	0	-	-	0.999324	**-97**
9	↓	↓	-	-	-	71	-	-	0	-	0.998983	**-103**
10	↓	↓	-	-	-	71	-	-	-	0	0.998976	**-107**
11	↓	↓	-	-	-	-	-	-	-	-	1.012841	**-79**
12	↓	↓	0	-	-	-	-	-	-	-	1.003716	**-77**
13	↓	↓	-	0	-	-	-	-	-	-	1.003941	**-83**
14	↓	↓	-	-	0	-	-	-	-	-	1.002843	**-82**
15	↓	↓	-	-	-	0	-	-	-	-	0.998815	**-80**
16	↓	↓	-	-	-	-	0	-	-	-	1.008281	**-80**
17	↓	↓	-	-	-	-	-	0	-	-	1.002018	**-80**
18	↓	↓	-	-	-	-	-	-	0	-	1.007749	**-78**
19	↓	↓	-	-	-	-	-	-	-	0	1.007745	**-81**
20	1291	560	-	-	-	-	-	-	-	-	1.000608	**-71**
21	↓	570	-	-	-	-	-	-	-	-	1.000034	**-80**
22	1230	565	-	-	-	0	-	-	-	-	0.992755	**-84**
23	↓	↓	-	-	-	23	-	-	-	-	0.993162	**-87**
24	↓	↓	-	-	-	46	-	-	-	-	0.994555	**-93**
25	↓	↓	-	-	-	69	-	-	-	-	0.997369	**-104**
26	↓	↓	-	-	-	92	-	-	-	-	1.000279	**-102**
27	↓	↓	-	-	-	115	-	-	-	-	1.002542	**-94**
28	↓	↓	-	-	-	138	-	-	-	-	1.004163	**-88**
29	↓	↓	-	-	-	161	-	-	-	-	1.005300	**-84**
30	↓	↓	-	-	-	184	-	-	-	-	1.006073	**-82**
31	↓	↓	-	-	-	207	-	-	-	-	1.006468	**-79**
32	↓	↓	-	-	-	-	-	-	-	-	1.006584	**-80**
											Average	**-88**

Note that for the integral rod worth cases, and several criticals where bank D was partially inserted, the axial mesh was manually modified to align with the Bank D poison tip. The largest effect was 31 pcm.

Figure 5-1 contains the MPACT results for the ten critical configurations for the WBN1 ZPPT, along with updated KENO, Insilico, and NEXUS results created from Reference 3. A -57 pcm correction is added to account for thermal expansion, and a -39 to -53 pcm correction was used for the SC and SD Bank criticals and worths to account for rotational symmetry (Ref. 3). The average reactivity error for MPACT is slightly low at -225 pcm, but consistent with the observed trends relative to CE KENO-VI.

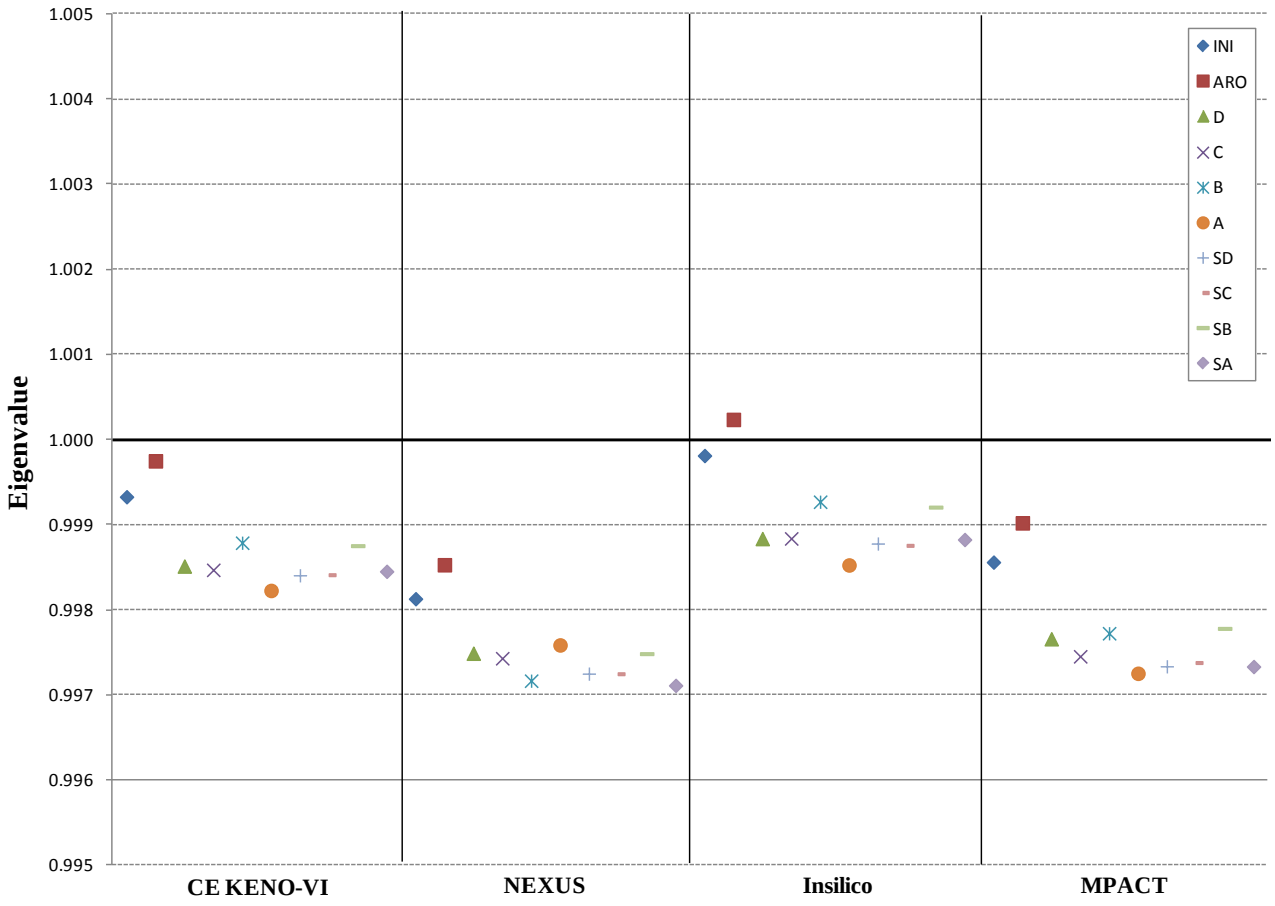

Figure 5-1: Problem 5 – Ten Criticals for WBN1 ZPPTs

The eight control rod bank worth calculations are provided in Figure 5-2. For each code, including MPACT, the measured worths are inferred from the reference bank critical position using calculated shadow factors, and to be consistent, each code was used to calculate those factors. Though the Bank A error is slightly large, it is consistent with KENO and Insilico. In fact, the predicted bank worths between KENO and MPACT are all less than 1%.

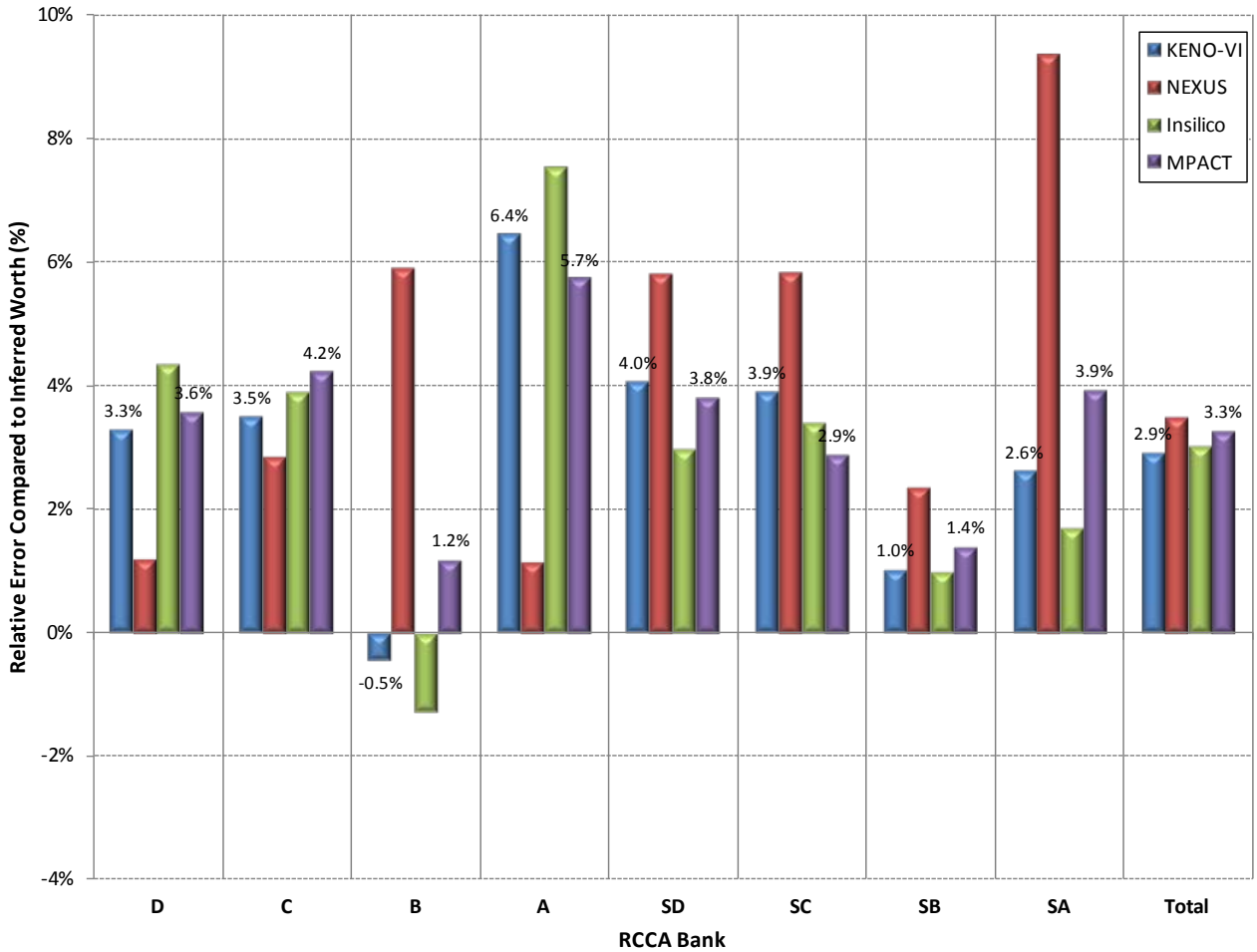

Figure 5-2: Problem 5 – RCCA Bank Worths for WBN1 ZPPTs

The WBN1 Differential Boron Worth (DBW) and Isothermal Temperature Coefficient (ITC) are calculated with MPACT and compared to KENO, Insilico, and NEXUS (from Reference 3) in Tables 5-2 and 5-3. The ITC is significantly more negative than the measured value, but is reasonable close to the value calculated with KENO-VI.

Table 5-2: Problem 5 MPACT Differential Boron Worth Results

Result	DBW (pcm/ppmB)	Difference (pcm/ppmB)
Measured	-10.77	--
CE KENO-VI	**-10.21**	**0.56**
NEXUS	-10.12	0.65
Insilico	-10.16	0.61
MPACT	**-10.16**	**0.61**

Table 5-3: Problem 5 MPACT Isothermal Temperature Coefficient Results

Result	ITC (pcm/F)	Difference (pcm/F)
Measured	-2.17	--
CE KENO-VI	**-3.18**	**-1.01**
NEXUS	-2.20	-0.03
Insilico	-3.99	-1.82
MPACT	**-3.72**	**-1.55**

The measurement of the Bank D worth was performed by continuous insertion during a system dilution and was measured by the plant reactimeter. While the measured results have not yet been released, MPACT results are compared in the figures below to the integral bank worth curve calculated by KENO. Note again that due to errors from the rod tip homogenization (up to 21 pcm), the axial mesh boundaries have been manually aligned with the control rod poison tip to reduce the eigenvalue error. These cases were not used for power distribution comparison due to relatively high power distribution uncertainties in the KENO solution.

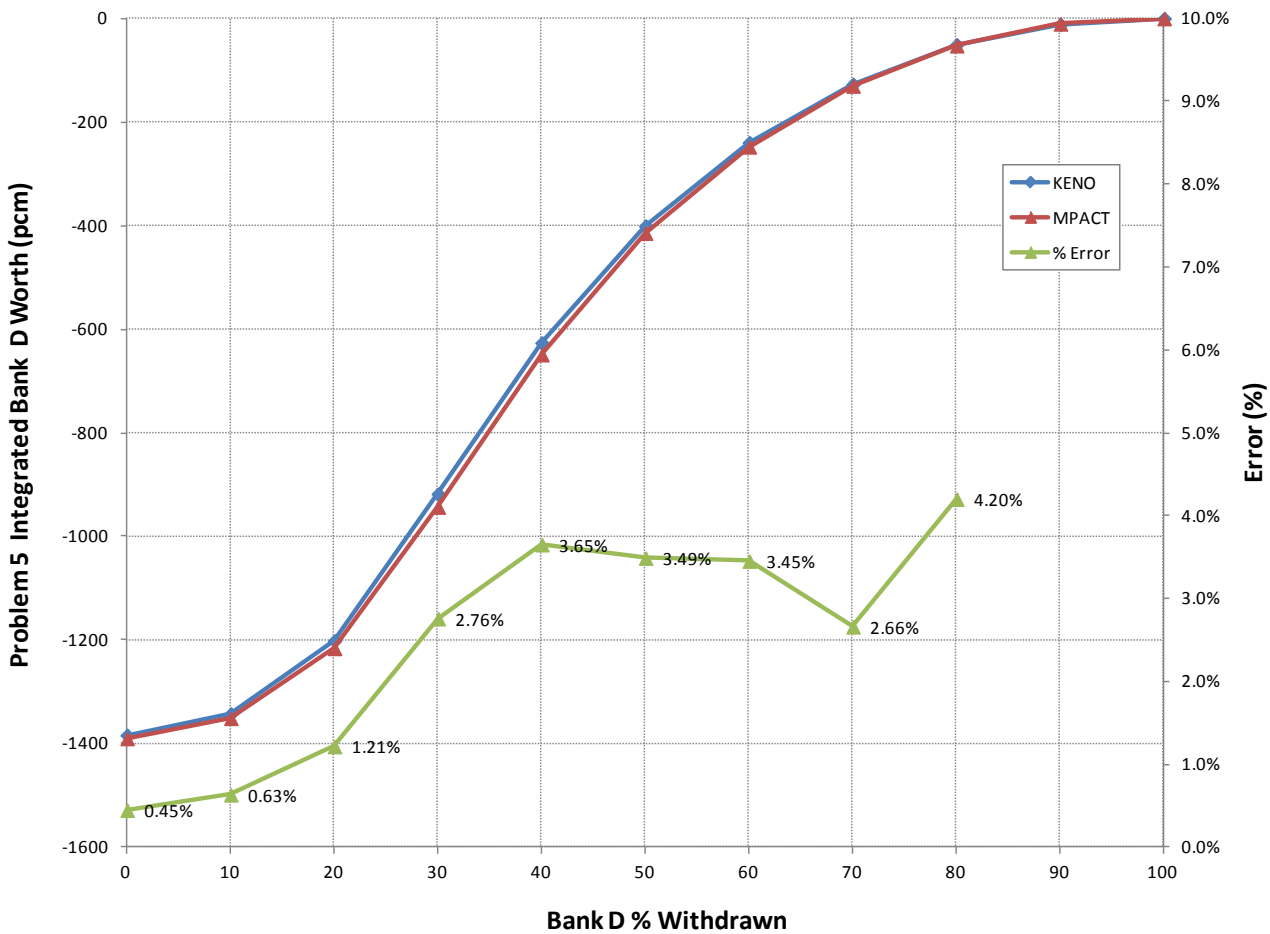

Figure 5-3: Problem 5 Bank D Integral Rod Worth Comparison

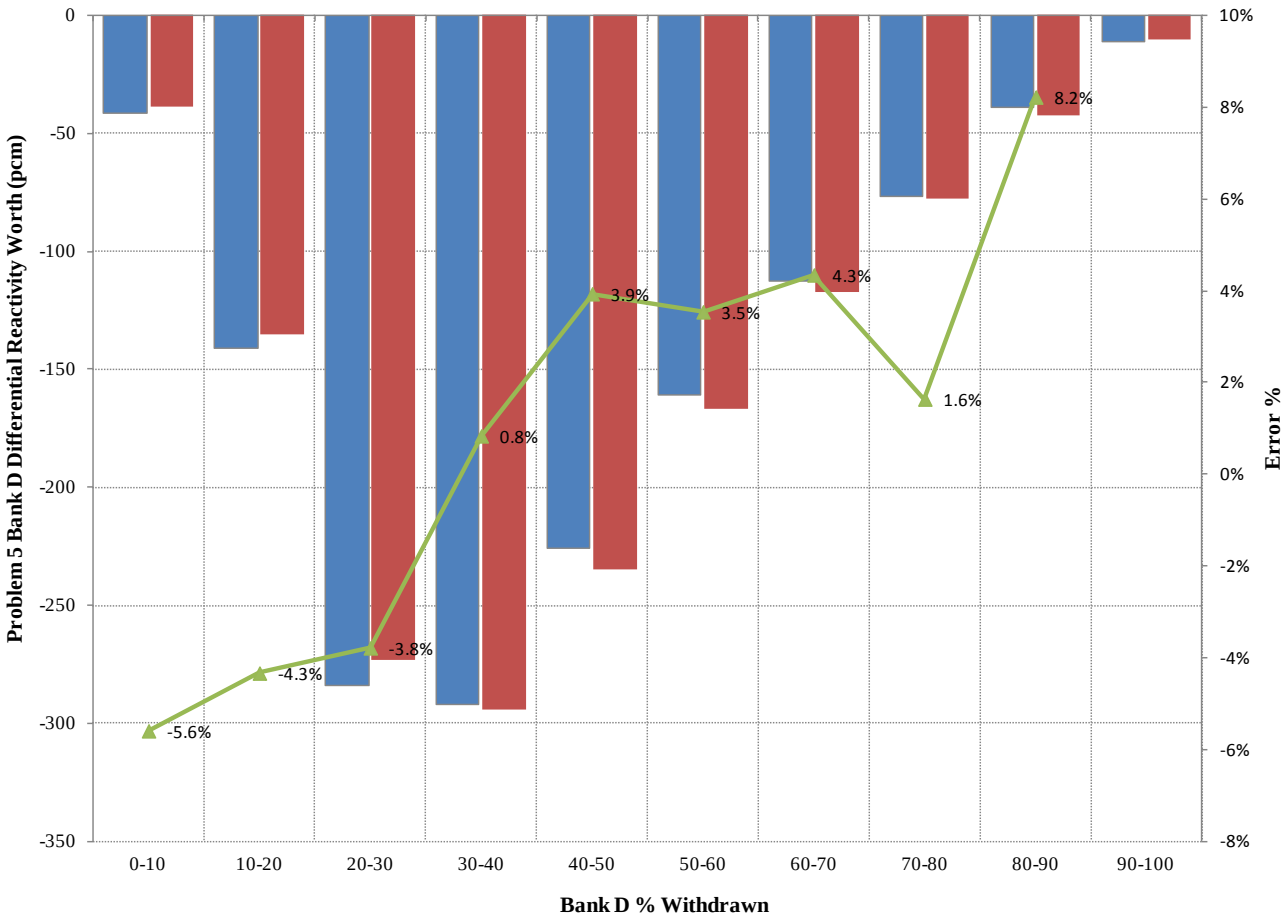

Figure 5-4: Problem 5 Bank D Differential Rod Worth Comparison

Finally, some power distributions comparisons between MPACT and KENO are provided in the following figures. For each one, the RMS of that power distribution will be provided in the figure as well. Note that these comparisons are performed without incore instrumentation and with Bank D at the initial critical position of 167 steps withdrawn. Please see Reference 2 for discussion of the uncertainties in the reference distributions.

Also, note that the reference solution contains additional radial core structure such as the core barrel and neutron pads, while MPACT does not. This is expected to result in a small deviation in pin and assembly power in the assemblies closest to the neutron pad on the core diagonal axis.

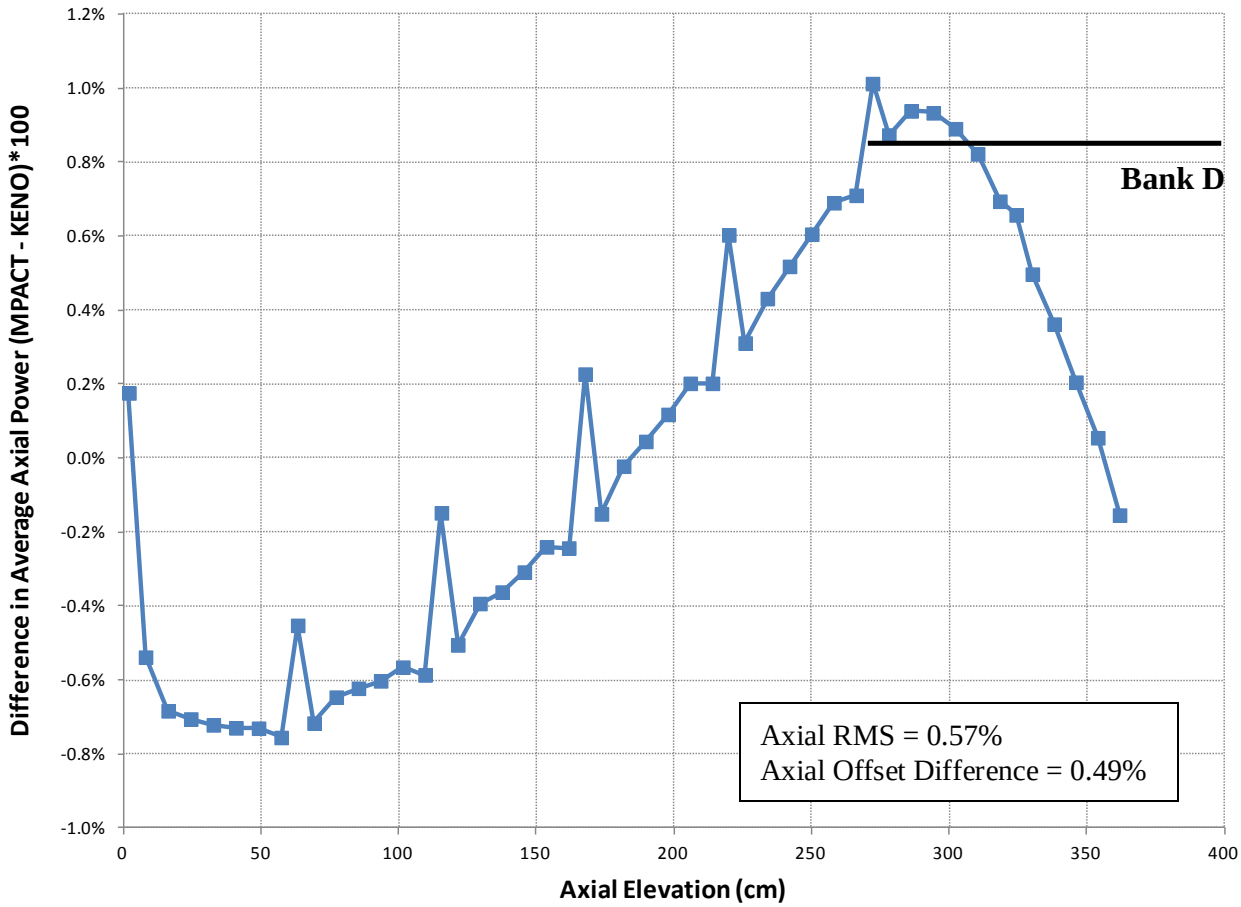

Figure 5-5: Problem 5 Axial Power Distribution Comparison

MPACT Powers

0.944					
0.918	0.993				
1.014	0.908	1.061			
0.985	1.078	1.041	1.158		
1.061	1.048	1.172	1.085	1.232	
1.051	1.161	1.154	1.149	0.897	0.911
1.086	1.071	1.105	1.052	0.944	0.625
0.799	0.912	0.809	0.660		

Max: 1.232 **Avg: 1.000**

Differences

-0.48%					
-0.10%	-0.39%				
-0.37%	-0.05%	-0.39%			
-0.03%	-0.35%	-0.03%	-0.40%		
-0.35%	0.06%	-0.27%	-0.02%	-0.50%	
0.28%	-0.06%	0.19%	-0.23%	-0.04%	-0.18%
0.23%	0.59%	0.09%	0.27%	-0.15%	-0.44%
0.62%	0.54%	0.44%	0.11%		

Max: 0.62% **Min: -0.50%** **RMS: 0.30%**

Figure 5-6: Problem 5 Radial Assembly Power Distribution Results

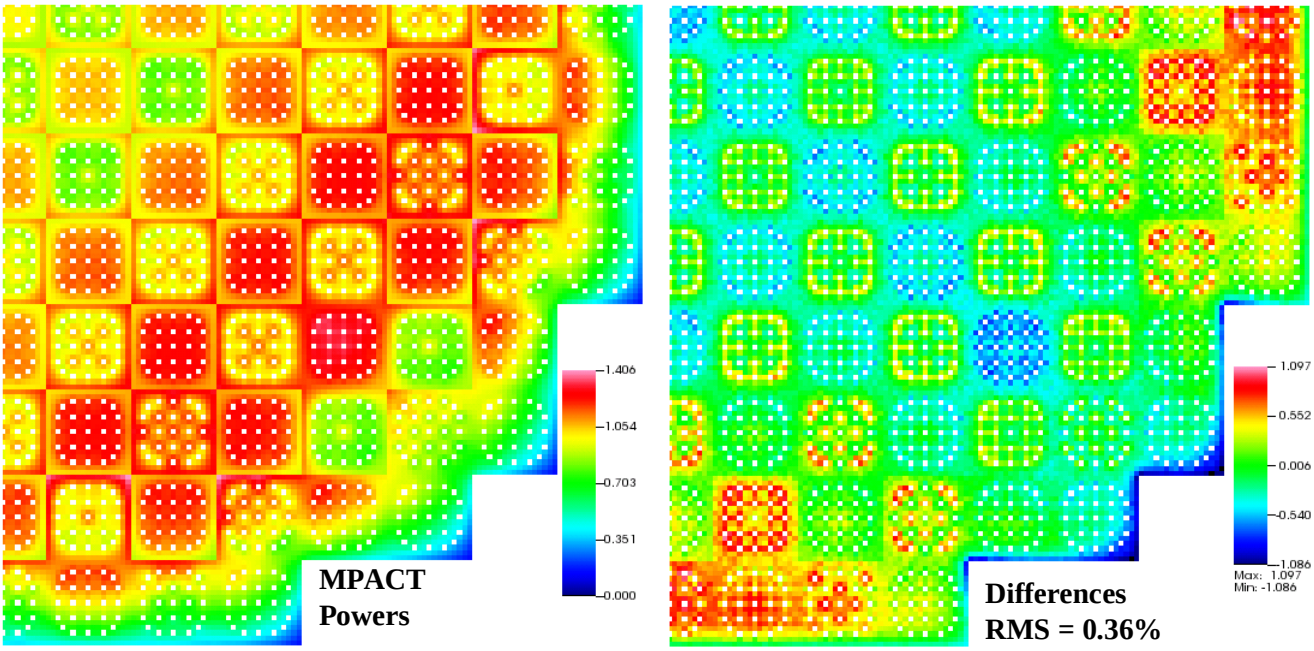

Figure 5-7: Problem 5 Radial Pin Power Distribution Results

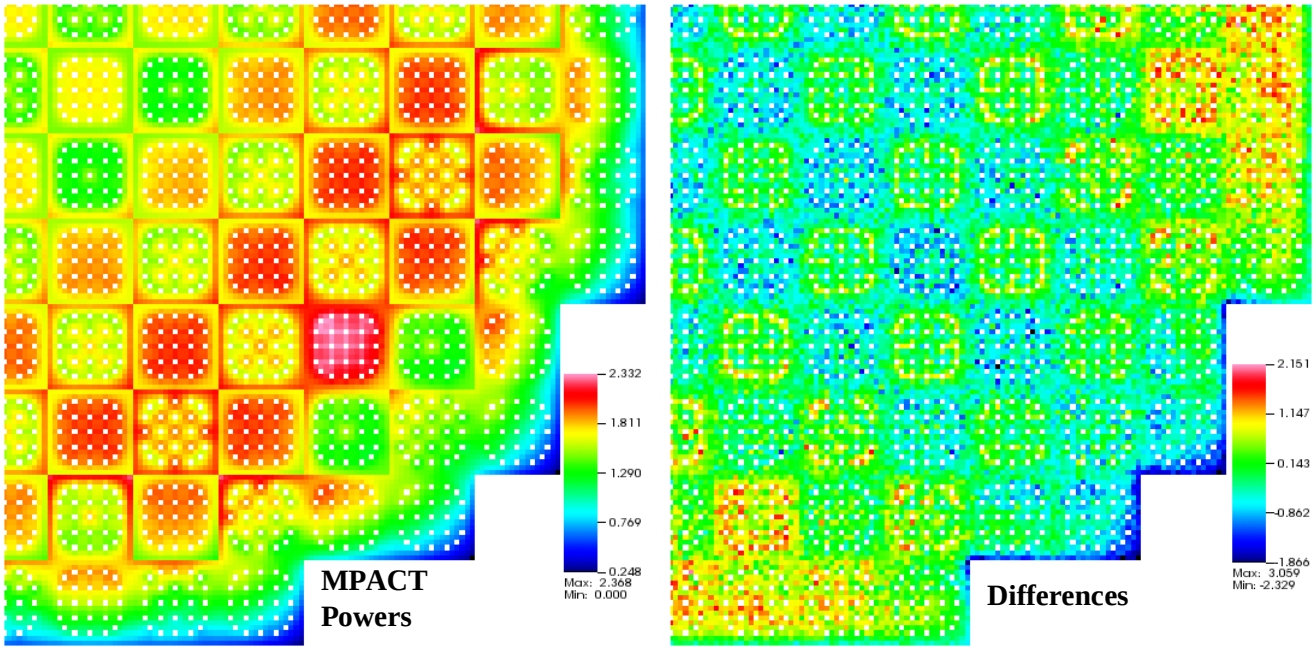

Figure 5-8: Problem 5 Mid Plane Pin Power Distribution Results

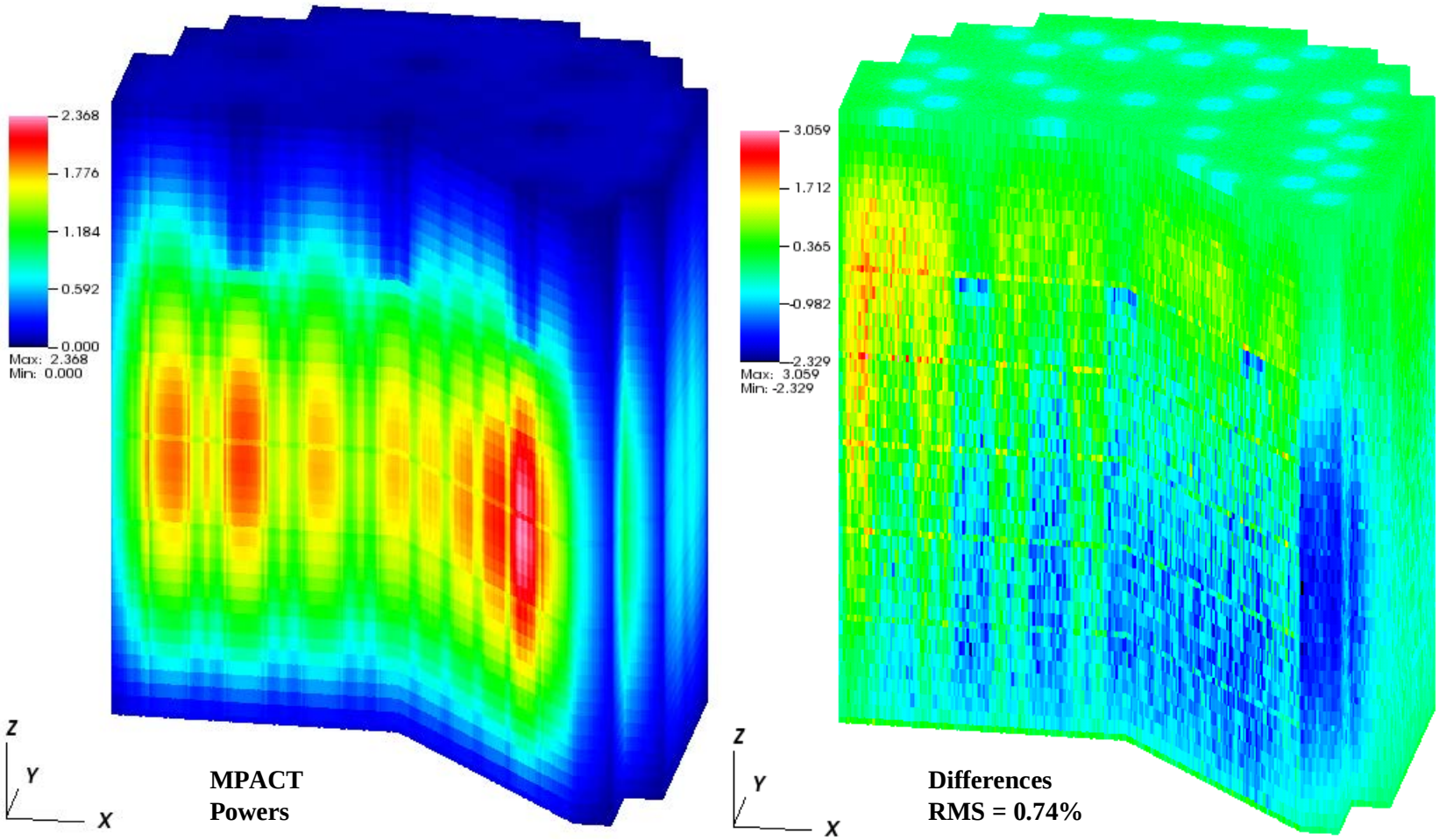

Figure 5-9: Problem 5 3D Pin Power Distribution Results

6. PROBLEM 4-2D – 2D 3X3 LATTICES

Table 6-1 contains the eigenvalue and fission rate distribution results for the 2D 3x3 cases, included in the Miscellaneous Benchmarks section of the reference specification (Ref. 2). Also, the percent error in control rod reactivity worth relative to the reference solution is also included. Each case was run with 72 processors on three EOS compute nodes.

Table 6-1: Problem 4-2D MPACT Results

Case	Control Type	Reference (± 2 pcm)	k-eff (pcm)	Pin RMS (%)	Pin Max (%)	Assy RMS (%)	Assy Max (%)	Rod Worth Error (%)	Run Time (secs)
4A-2D	None	1.010238	**-61**	**0.13%**	**0.35%**	**0.08%**	**0.10%**	**---**	107
4B-2D	AIC	0.983446	**-77**	**0.13%**	**0.43%**	**0.07%**	**0.16%**	**0.72%**	120
4C-2D	B_4C	0.980291	**-64**	**0.13%**	**0.32%**	**0.07%**	**0.07%**	**0.24%**	120
Average			**-67**	**0.13%**	**0.37%**	**0.07%**	**0.11%**	**---**	116

Figures 6-1 to 6-3 display the pin power distribution results. Though some biases are evident for control and Pyrex rods, the differences are relatively small, especially given the dramatic variation in power distribution across the controlled cases. Note that the assembly powers are not provided as the differences are insignificant, as shown in Table 6-1.

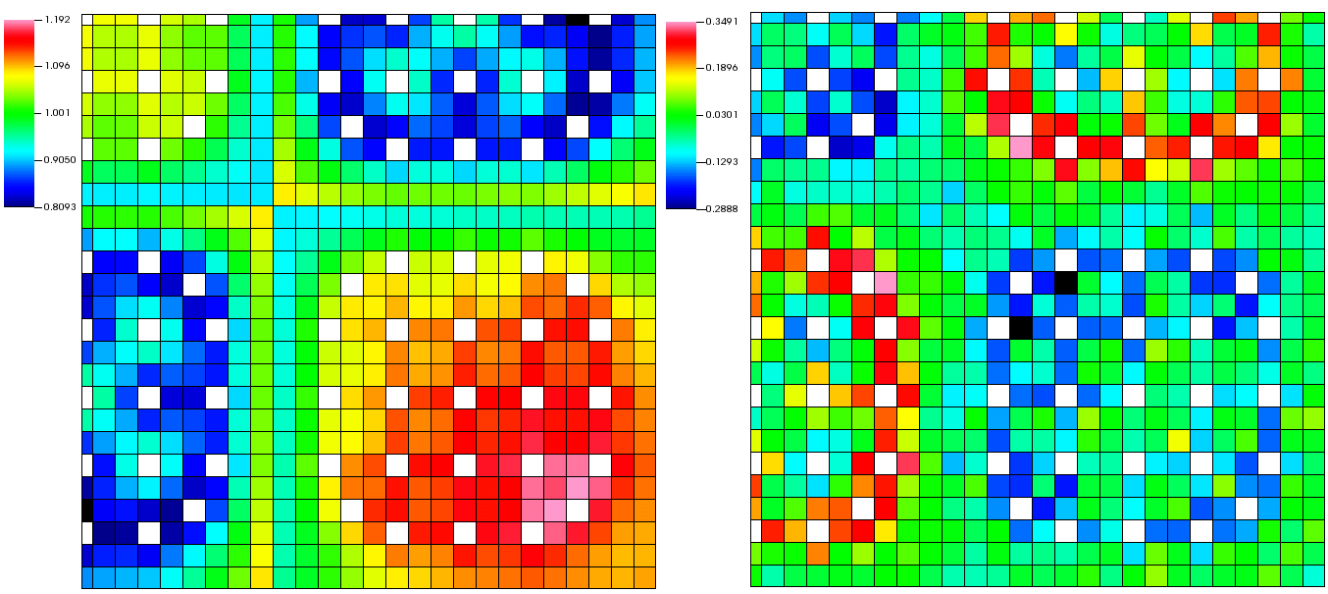

Figure 6-1: Problem 4A-2D (Uncontrolled) Pin Power Distribution Results

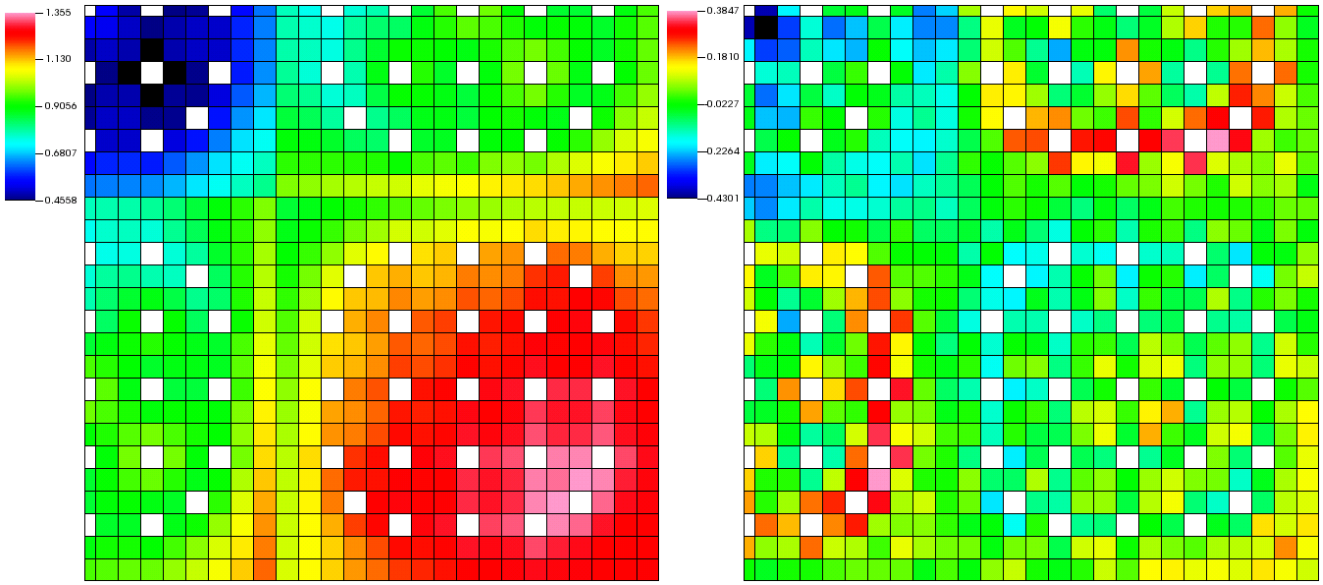

Figure 6-2: Problem 4B-2D (AIC) Pin Power Distribution Results

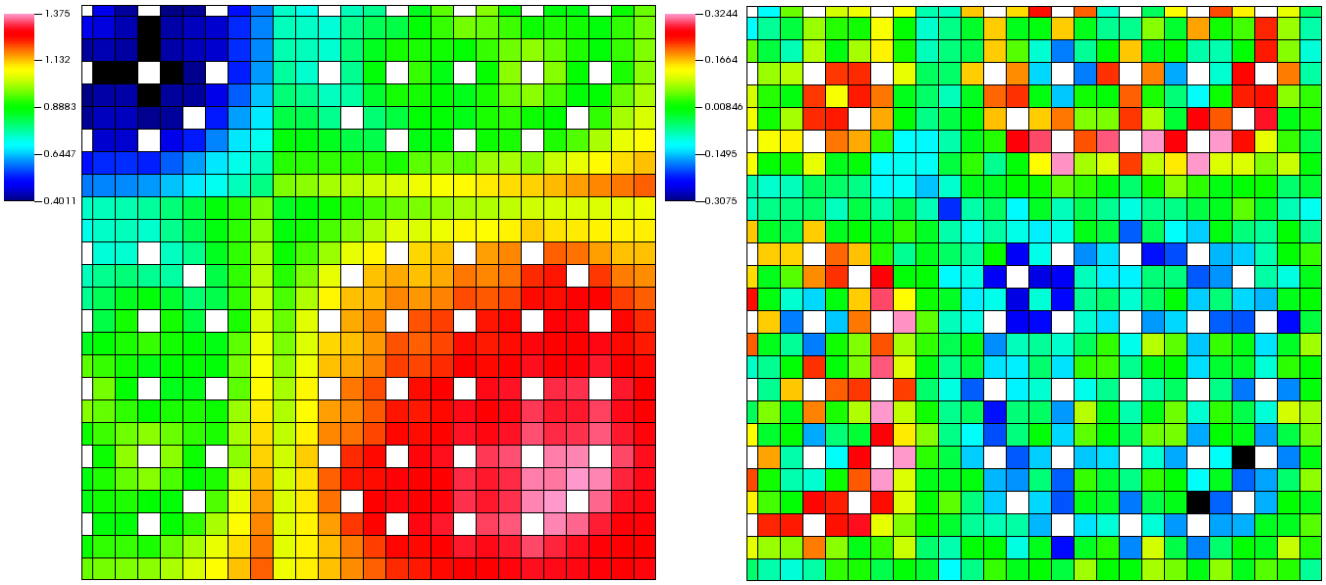

Figure 6-3: Problem 4C-2D (B_4C) Pin Power Distribution Results

7. PROBLEM 5-2D – 2D CORE

Table 7-1 contains the eigenvalue and fission rate distribution results for the WBN1 2D core cases, included in the Miscellaneous Benchmarks section of the reference specification. Also, the percent error in control rod reactivity worth relative to the reference solution is also included. Each case was run with 448 processors on 14 EOS compute nodes.

For comparison purposes, the reference case selected contained only the baffle for the radial reflector regions, not the core barrel, neutron pads, or vessel.

Table 7-1: Problem 5-2D MPACT Results

Case	Bank D Type	Reference (± 1 pcm)	k-eff (pcm)	Pin RMS (%)	Pin Max (%)	Assy RMS (%)	Assy Max (%)	Rod Worth Error (%)	Run Time (mins)
5A-2D	None	1.004040	**-50**	**0.49%**	**1.25%**	**0.46%**	**0.97%**	**---**	21.3
5B-2D	AIC	0.991468	**-52**	**0.75%**	**1.68%**	**0.71%**	**1.24%**	**0.3%**	21.4
5C-2D	B_4C	0.990194	**-47**	**0.70%**	**1.82%**	**0.66%**	**1.23%**	**-0.1%**	21.6
Average			**-50**	**0.65%**	**1.59%**	**0.61%**	**1.15%**	**---**	21.4

Figures 7-1 to 7-3 display the core power distributions calculated by MPACT along with the absolute difference in pin powers from the reference solution, in percent (%). In all cases, a small radial tilt of 0.8-1.0% is apparent, with MPACT under-predicting the power in the core center and over-predicting that of the peripheral locations. Also, in these figures, the assembly average powers and differences are provided as labels in the plots.

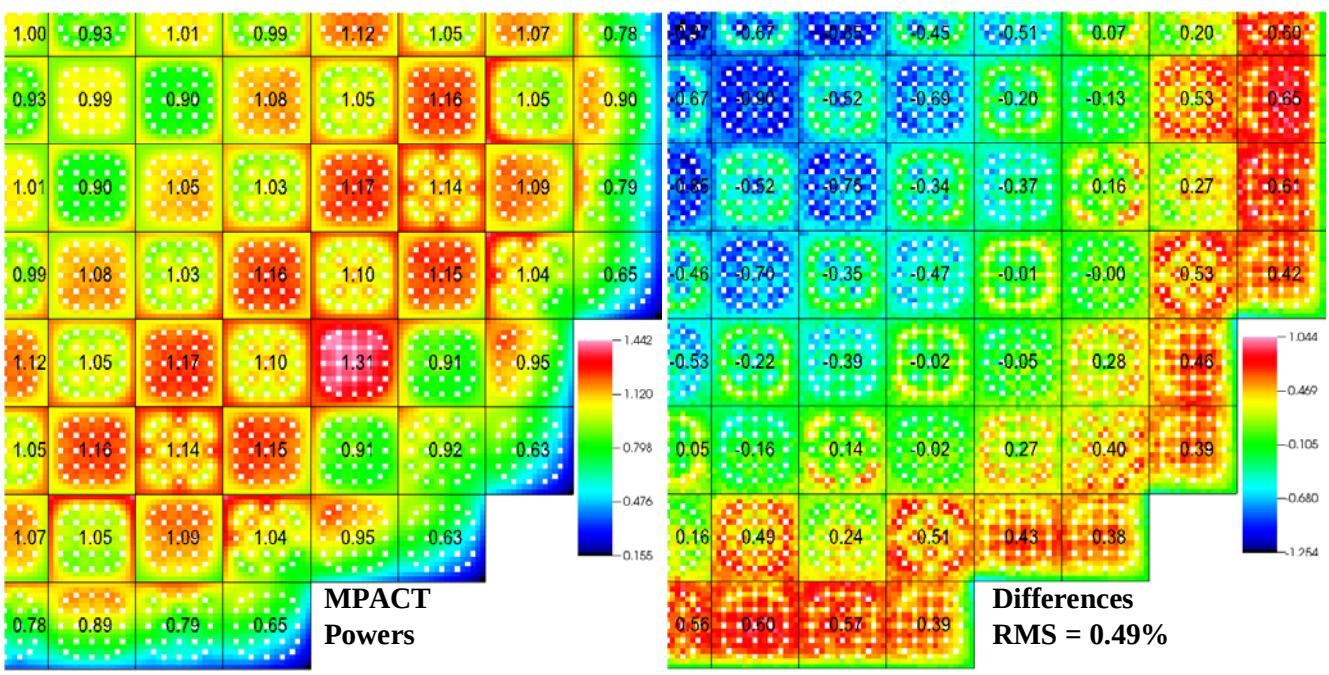

Figure 7-1: Problem 5A-2D (Uncontrolled) Pin Power Distribution Results

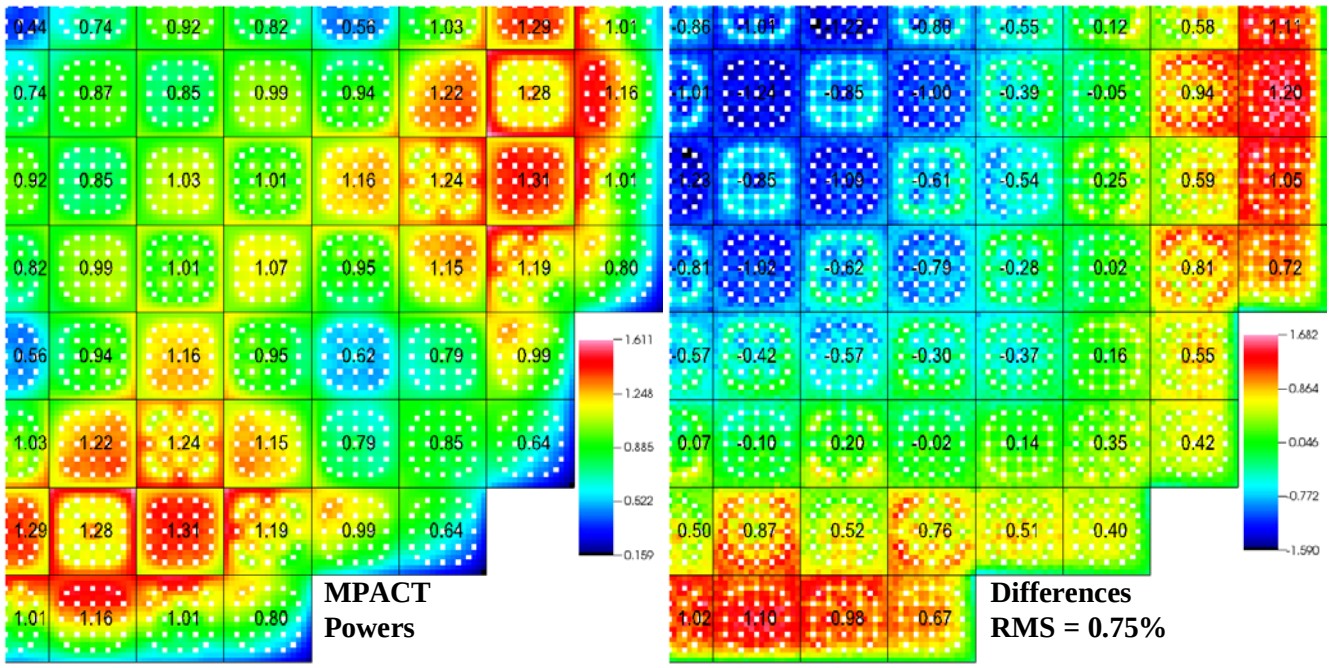

Figure 7-2: Problem 5B-2D (AIC) Pin Power Distribution Results

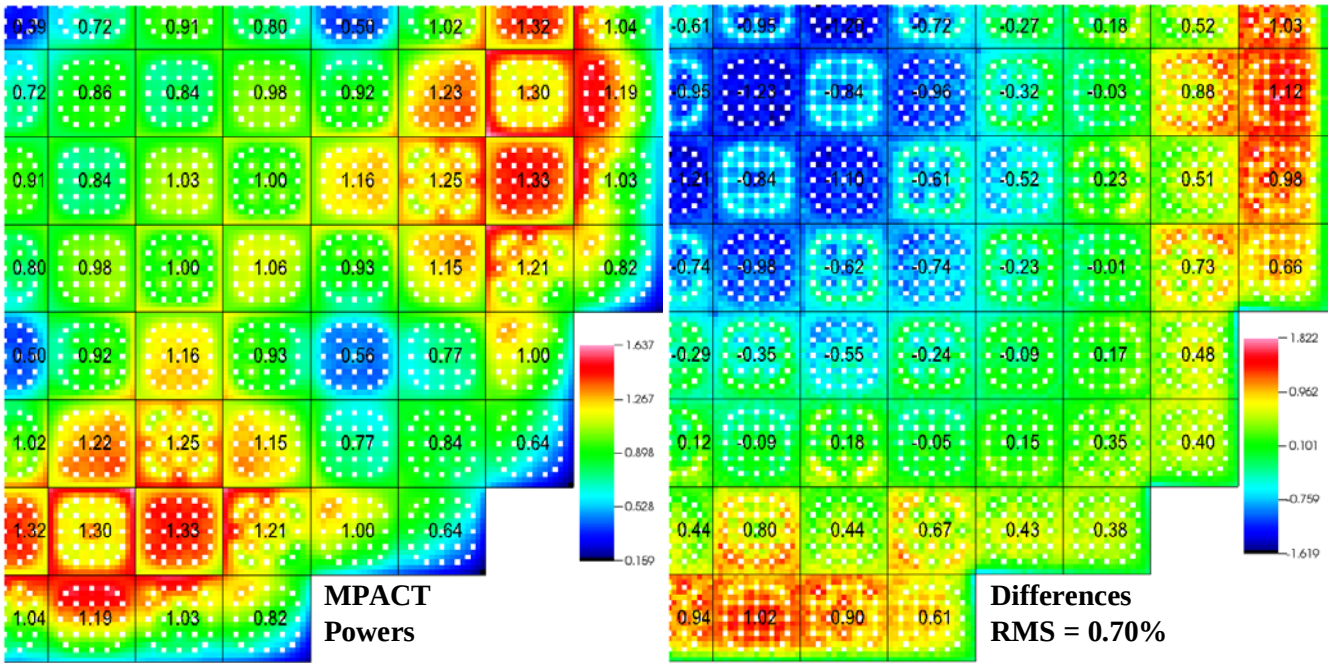

Figure 7-3: Problem 5C-2D (B_4C) Pin Power Distribution Results

8. ISSUES AND FEEDBACK

During this testing and benchmarking activity, the following items were noted which will need to be addressed in the future as MPACT becomes more ready for production applications:

1. A small temperature reactivity bias of approximately -160 pcm exists for increasing temperature cases between 600K and 1200K.
2. A small reactivity bias exists for lattices with AIC control rods. AIC tips are used for WBN1 so this could impact some of the ZPPT results and the axial power shapes.
3. A small reactivity bias and radial power tilt exists for grid spacer lattices. This is likely just due to inconsistencies between the modeling approach in MPACT vs. that taken in the reference solution.
4. The results for IFBA bearing rods and lattices are very good, yet they require a decrease of 10x in the MOC ray spacing, which results in a 5x increase in runtime. Fortunately, WBN1C1 does not have IFBA.
5. For uncontrolled 3D problems, an approximate 0.5% power bias exists for spacer grid axial locations. This bias is independent from item 3 above.
6. For Problems 4 and 5 with RCCAs, an approximate 1.0%-1.5% axial tilt exists with MPACT over predicting the power at the top of the problem. This could be related to the AIC bias (2 above) and will be further investigated.
7. For Problems 5 and 5-2D, a small radial power tilt of approximately 0.5-1.0% exists, with MPACT under-predicting the power in the core center as compared to the reference solution.
8. For controlled problems, the current method of homogenizing control rod tips can lead to significant eigenvalue errors (+80 pcm for Problem 4 and +30 pcm for Problem 5) and very large pin power errors (up to 49%). Manual addition of planes at the rod tip is an unsatisfactory solution, and this method could result in thin planes which may degrade the solution stability. A new methodology needs to be developed to handle control rod tips/boundaries that fall within an axial plane.
9. Corrections for thermal expansion and rotational symmetry were applied in this analysis based on nodal code results in Reference 3.
10. The quarter-core runtime will need to be improved for modeling reactor operation with T/H feedback. The cases here of 1-1.5 hours are acceptable but they are at zero power conditions.

REFERENCES

1 Collins, B., et. al., "Application of MPACT 2D/1D to AMA Benchmark Problem 5", Revision 0, CASL-U-2013-0273-000, CASL, November 30, 2013.

2 A.T. Godfrey, "VERA Core Physics Benchmark Progression Problem Specifications", Revision 3, CASL-U-2012-0131-003, CASL, March 31, 2014.

3 Gehin, J. C, et. al., "Operational Reactor Modal Demonstration with VERA: Watts Bar Unit 1 Cycle 1 Zero Power Physics Tests", Revision 2, CASL-U-2013-0105-001, CASL, August, 2013.