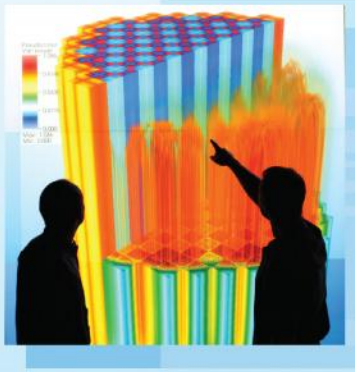
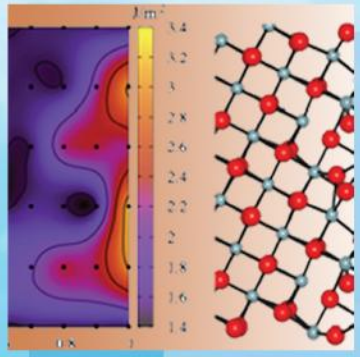
CASL-U-2012-0172-000

Power uprates
and plant life extension



Engineering design
and analysis

Science-enabling
high performance
computing



Fundamental science

Plant operational data

Consortium for Advanced Simulation of LWRs

Analysis of Two-Dimensional Lattice Physics Verification Problems with MPACT

Andrew Godfrey, ORNL
Fausto Franceschini,
Westinghouse Electric Company LLC
Scott Palmtag, Core Physics
Julie Stout, ORNL

Advanced Modeling Applications
December 21, 2012

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

REVISION LOG

Revision	Date	Affected Pages	Revision Description
0	12/21/2012	All	Original Issue

Document pages that are:

Export Controlled _None_

IP/Proprietary/NDA Controlled_None_

Sensitive Controlled_None_

Requested Distribution:

To: N/A

Copy: N/A

EXECUTIVE SUMMARY

CASL is developing the Virtual Environment for Reactor Applications (VERA) as a key capability to support the analysis of the CASL Challenge Problems. VERA will include a range of physics modeling capabilities necessary to model reactors, including neutronics, thermal hydraulics, fuel performance, coolant chemistry, with development efforts underway in all of these areas. This report documents the application of the lattice physics capability available in MPACT v1.0. Lattice physics analyses are important to CASL for several reasons:

- The nuclear power industry regularly performs 2D lattice calculations. The ability of VERA to perform these types of calculations is critical.
- The Advanced Modeling Applications Focus Area has defined the VERA requirements for 2D lattice capability as part of the Core Physics Benchmark Progression Problems.
- Several of the neutronics methods planned for VERA include a spatially hybrid approach to the 3D neutron transport solution, combining solutions of 2D slices of the core coupled to some form of axial solution (i.e. 2D/1D or 2D/3D). Therefore, testing the performance of the 2D lattice features is critical to understanding how the coupled 2D and 3D solution methodology will perform.

Numerical validation of the lattice physics capability in MPACT (and its associated multi-group cross section library) is achieved by comparison of many lattice eigenvalues and normalized fission rate densities to solutions generated by two independent continuous energy (CE) Monte Carlo particle transport codes, KENO-VI and MCNP5. In addition, an analysis of a 2D 3x3 multi-assembly problem is performed and the control rod reactivity worth is also evaluated. In each of these cases MPACT is shown to provide solutions that are in excellent agreement with the reference solutions.

In addition to CE Monte Carlo results, comparisons are also made to the Westinghouse lattice physics code PARAGON. PARAGON is part of the Westinghouse in-house core physics suite that is qualified and routinely employed for the analysis of commercial PWRs. It relies on an extensive validation basis and comparison against measurements of US and world-wide PWRs and critical experiments and is representative of the current industry state-of-the-art lattice physics tools. Comparisons between the results from PARAGON and MPACT also demonstrate that MPACT is performing very well.

After application and testing of MPACT v1.0 on many lattice physics problems, encompassing a wide range of fuel temperatures, integral and discrete burnable absorbers, control rods, and a multi-assembly controlled configuration, it is evident that MPACT has a strong capability for solving these types of problems. The figure below summarizes AMA's assessment of the capabilities of MPACT v1.0 as a result of this analysis (with details in Appendix E).

AMA Core Physics Benchmark Progression Problems

	1	2	3	4	5
Development Status	83%	71%			
Analysis Status	100%	100%			
Total Status	**85%**	**76%**			

CONTENTS

REVISION LOG ii

EXECUTIVE SUMMARY iii

CONTENTS v

FIGURES vi

TABLES viii

ACRONYMS ix

1. INTRODUCTION 1

2. PURPOSE 3

3. COMPUTER CODES 4
3.1 MPACT v1.0 4
3.2 KENO-VI 5
3.3 MCNP5 6
3.4 PARAGON 6

4. RESULTS 8
4.1 Single Assembly Lattices 8
4.2 Multiple 2D Lattices 42

CONCLUSIONS and FEEDBACK 50

ACKNOWLEDGEMENTS 50

REFERENCES 51

APPENDIX A – EMAIL REGARDING MPACT v1.0 RELEASE 53

APPENDIX B –MPACT INPUT FOR 2D LATTICE 54

APPENDIX C –MPACT INPUT FOR 2D 3x3 56

APPENDIX D – PROBLEM 1 RESULTS 60

APPENDIX E – MPACT CAPABILITY ASSESSMENT 61

FIGURES

Figure 1: Ten AMA Core Physics Benchmark Progression Problems 2

Figure 2: Problem 2 Lattice Layouts (Octant Symmetry) 10

Figure 3: Problem 2A (565K) MPACT 60g Power Distribution Results 12

Figure 4: Problem 2B (600K) MPACT 60g Power Distribution Results 12

Figure 5: Problem 2C (900K) MPACT 60g Power Distribution Results 12

Figure 6: Problem 2D (1200K) MPACT 60g Power Distribution Results 12

Figure 7: Problem 2E (12 Pyrex) MPACT 60g Power Distribution Results 13

Figure 8: Problem 2F (24 Pyrex) MPACT 60g Power Distribution Results 13

Figure 9: Problem 2G (AIC) MPACT 60g Power Distribution Results 13

Figure 10: Problem 2H (B_4C) MPACT 60g Power Distribution Results 13

Figure 11: Problem 2I (Instrument Thimble) MPACT 60g Power Distribution Results 14

Figure 12: Problem 2J (Instrument and Pyrex) MPACT 60g Power Distribution Results 14

Figure 13: Problem 2K (Zoned and 24 Pyrex) MPACT 60g Power Distribution Results 14

Figure 14: Problem 2L (80 IFBA) MPACT 60g Power Distribution Results 14

Figure 15: Problem 2M (128 IFBA) MPACT 60g Power Distribution Results 15

Figure 16: Problem 2N (104 IFBA + 20 WABA) MPACT 60g Power Distribution Results 15

Figure 17: Problem 2O (12 Gadolinia) MPACT 60g Power Distribution Results 15

Figure 18: Problem 2P (24 Gadolinia) MPACT 60g Power Distribution Results 15

Figure 19: MPACT Eigenvalue Differences with B-VII Cross Sections 21

Figure 20: MPACT Pin Power RMS Differences with B-VII Cross Sections 21

Figure 21: MPACT Maximum Absolute Pin Power Differences with B-VII Cross Sections 22

Figure 22: MPACT Eigenvalue Differences with B-VI Cross Sections 22

Figure 23: MPACT Pin Power RMS Differences with B-VI Cross Sections 23

Figure 24: MPACT Maximum Absolute Pin Power Differences with B-VI Cross Sections 23

Figure 25: MPACT Problem 2A Power Distribution Comparisons 24
Figure 26: MPACT Problem 2B Power Distribution Comparisons 25
Figure 27: MPACT Problem 2C Power Distribution Comparisons 26
Figure 28: MPACT Problem 2D Power Distribution Comparisons 27
Figure 29: MPACT Problem 2E Power Distribution Comparisons.....28
Figure 30: MPACT Problem 2F Power Distribution Comparisons.....29
Figure 31: MPACT Problem 2G Power Distribution Comparisons 30
Figure 32: MPACT Problem 2H Power Distribution Comparisons 31
Figure 33: MPACT Problem 2I Power Distribution Comparisons.....32
Figure 34: MPACT Problem 2J Power Distribution Comparisons 33
Figure 35: MPACT Problem 2K Power Distribution Comparisons 34
Figure 36: MPACT Problem 2L Power Distribution Comparisons.....35
Figure 37: MPACT Problem 2M Power Distribution Comparisons 36
Figure 38: MPACT Problem 2N Power Distribution Comparisons 37
Figure 39: MPACT Problem 2O Power Distribution Comparisons 38
Figure 40: MPACT Problem 2P Power Distribution Comparisons.....39
Figure 41: Problem 4-2D Assembly, Pyrex, and Control Rod Arrangement 42
Figure 42: Problem 4-2D Reference Model (with AIC inserted) 43
Figure 43: Problem 4-2D Uncontrolled MPACT 60g Power Distribution Results 45
Figure 44: Problem 4-2D Controlled MPACT 60g Power Distribution Results 45
Figure 45: Problem 4-2D ENDF/B-VII Uncontrolled MPACT Pin Power Differences 46
Figure 46: Problem 4-2D ENDF/B-VII Controlled MPACT Pin Power Differences 47
Figure 47: Problem 4-2D ENDF/B-VI MPACT Pin Power Differences 48

TABLES

Table 1: Problem 2 Calculations 9

Table 2: Problem 2 Input Specification 9

Table 3: Problem 2 ENDF/B-VII Eigenvalue Results 11

Table 4: Problem 2 ENDF/B-VI Eigenvalue Results 11

Table 5: MPACT Runtime Performance for Problem 2 16

Table 6: MPACT Differences with ORNL ENDF/B-VII 60g Library 18

Table 7: MPACT Differences with HELIOS ENDF/B-VI 47g Library 20

Table 8: MPACT Results Using ESSM Compared to KENO-VI 41

Table 9: MPACT Runtime Performance for Problem 4-2D 43

Table 10: MPACT Eigenvalue Comparisons for Problem 4-2D 44

Table 11: MPACT Rod Worth Comparisons for Problem 4-2D 44

Table 12: MPACT Power Distribution Statistics for Problem 4-2D 44

Table D1: Problem 1 MPACT ENDF/B-VII Eigenvalue Results 60

Table D2: Problem 1 MPACT ENDF/B-VI Eigenvalue Results 60

Table E1: Assessment of MPACT for Problems 1 and 2 61

ACRONYMS

2D	Two Dimensional
3D	Three Dimensional
AMA	Advanced Modeling Applications
BOC	Beginning of Cycle
CASL	Consortium for Advanced Simulation of Light Water Reactors
CE	Continuous energy
CMFD	Coarse Mesh Finite Difference
CP	Collision Probability
ESSM	Embedded Self-Shielding Method
HZP	Hot Zero Power
LWR	Light Water Reactor
MG	Multi-group (as in cross sections)
MOC	Method of Characteristics
ORNL	Oak Ridge National Laboratory
PCM	Percent Mill (in the case, 10^5 times Δk)
PWR	Pressurized Water Reactor
RMS	Root Mean Square
TVA	Tennessee Valley Authority
UM	University of Michigan
U.S. NRC	United States Nuclear Regulatory Commission
VERA	Virtual Environment for Reactor Applications

1. INTRODUCTION

Lattice physics refers to the simulation and analysis of the neutronic behavior of a two-dimensional (2D) slice of a nuclear fuel assembly. For decades, this type of analysis has been used to provide homogenized cross sections to three-dimensional (3D) nodal diffusion codes for the simulation, benchmarking, and licensing of nuclear power reactors. From an industrial nuclear analysis perspective, the 2D lattice calculation provides the foundation for all core analyses, including core design, core monitoring, even transient or accident analysis. Therefore it is critical that any new reactor analysis software be able to provide similar capabilities.

Typical lattice physics calculations are engineered to perform a variety of functions quickly and accurately, including:

- Material definitions
- Microscopic cross section processing
- Many-group neutron transport and eigenvalue calculation
- Gamma transport
- Relative pin power distribution calculation
- Incore instrumentation response
- Isotopic depletion and decay
- Homogenized few-group macroscopic cross section calculations

U.S. NRC approved methodologies for reactor core analysis typically depend on the parameterized results of 2D lattice calculations. The core reactivity and 3D assembly powers are calculated with the few-group homogenized macroscopic cross sections. The power of the individual fuel rods in the core are approximated by overlaying the shape of the lattice pin power distributions with the calculated 3D assembly powers (aka pin power reconstruction). Therefore, the capability to accurately perform lattice physics calculations is an essential feature of any recent and modern core analysis software.

In order to achieve a more advanced simulation of light water reactors (LWRs), CASL needs to apply most of these lattice physics capabilities to the entire 3D reactor core. By elimination of the coarse mesh 3D diffusion methods, better simulation of off-nominal conditions, heterogeneous core loadings, and fine-mesh pin local phenomena can be achieved. Conversely the negative aspect of reaching this fidelity is an extreme increase in the required computational resources and runtimes for full core 3D problems. By developing this advanced simulation capability, the lattice physics portion of current methodologies will expand to be the primary neutronic component of the advanced tools.

CASL's Virtual Environment for Reactor Applications (VERA) is being developed and tested against a set of ten basic problems designed to demonstrate its progressing capability to perform a steady-state fuel cycle depletion. These problems are shown below in Figure 1. The second of these progression benchmarks is the ability to perform a lattice physics calculation. The ability to solve this problem will provide critical feedback to the VERA developers and demonstrate the capability to users.

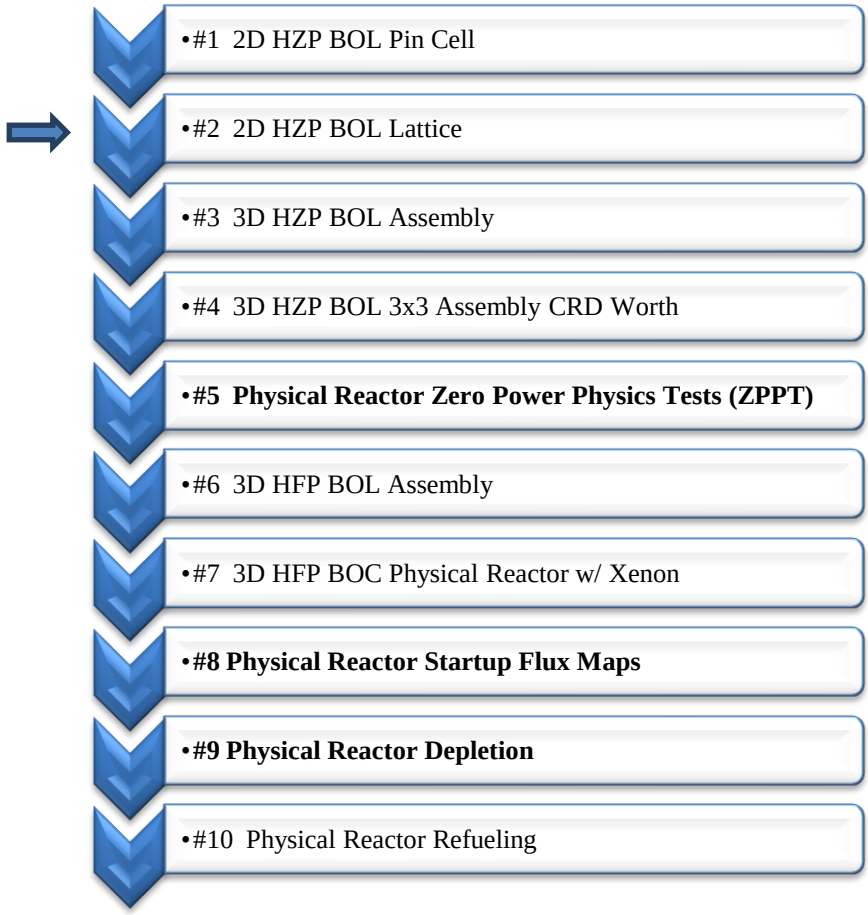


Figure 1: Ten AMA Core Physics Benchmark Progression Problems
(Ref. 22)

Note that Problem 2 does NOT require all of the features of typical lattice physics codes, especially those features that support nodal code methodologies (few-group condensation, nodal macroscopic cross sections, depletion, etc.). Rather, these problems represent a basic capability to perform two-dimensional lattice calculations and to allow for verification of results against higher fidelity calculations (such as continuous energy Monte Carlo solutions).

2. PURPOSE

This report documents the initial user testing and lattice physics capability available in MPACT v1.0 (Ref. 1, 2, and 3). As described in the previous section, lattice physics analyses are important to CASL for several reasons:

- The nuclear power industry regularly performs 2D lattice calculations. The ability of VERA to perform these types of calculations is critical.

- The Advanced Modeling Applications Focus Area (AMA) has defined the VERA requirements (Ref. 22) for 2D lattice capability as part of the Core Physics Benchmark Progression Problems (Ref. 4 and Problem #2 in Figure 1).

- Several of the neutronics methods planned for VERA include a spatially hybrid approach to the 3D neutron transport solution, combining solutions of 2D slices of the core coupled to some form of axial solution (i.e. 2D/1D or 2D/3D). Therefore, testing the performance of the 2D lattice features is critical to understanding how the coupled 2D and 3D solution methodology will perform.

The primary features being tested for Problem 2 are the ability to model typical PWR lattice assemblies consisting of fuel rods, guide tubes, instrument tubes, various burnable absorbers, control rod absorber types, and inter-assembly gaps. These abilities are verified by successfully performing the specified calculations and producing accurate results in comparison to reference solutions for the assembly reactivity, by comparison of eigenvalue, and the assembly relative fission reaction rate distribution. It is too early in VERA development to test some of the other lattice physics capabilities, such as the contribution to pin powers from gammas and isotopic depletion, which will be tested as the capabilities are developed. The execution performance of the code is also documented.

In addition to single assembly calculations, a 3x3 array of assemblies with and without a central reactivity control rod cluster assembly is tested, and the control rod reactivity worth is evaluated. Arrays of assemblies provides a more challenging and relevant simulation environment of the actual core operating conditions than single assembly analyses, where reflective conditions at the assembly boundary are assumed.

Numerical validation of code capability is achieved by comparison of results to the numerical reference solutions provided in Problem 2 (Ref. 4). The reference solutions are calculated with a continuous energy (CE) Monte Carlo method of particle transport, eliminating approximations made by deterministic codes in multi-group (MG) cross section treatments, resonance self-shielding, and spatial geometric approximations and meshing. The reference solutions in Reference 4 are provided by the SCALE code KENO-VI (Ref. 5). In addition, calculations have been performed using MCNP5 (Ref. 6) and these results provide additional confidence on the reference values, especially since MCNP5 is widely used in the nuclear industry for code-to-code benchmarking.

In addition to CE Monte Carlo results, this report also includes comparisons to the Westinghouse lattice physics code PARAGON (Ref. 7). PARAGON is a deterministic transport code which is part of the Westinghouse in-house core physics suite licensed and routinely employed for the analysis of commercial PWRs (Ref. 20). It relies on an extensive validation basis and comparison against measurements of US and world-wide PWRs and critical experiments and is representative of the

industry current state-of-the-art lattice physics tools. Comparisons of the VERA tools to a licensed code with extensive and certified reliability across the variety of fuels and lattices that can be expected in commercial PWRs proved invaluable.

Since PARAGON is NOT part of VERA its results are proprietary to Westinghouse. In this nonproprietary document, PARAGON information and results have been removed where there are backets []. A proprietary version of this report, CASL-P-2012-0172-000, contains the detailed PARAGON results.

3. COMPUTER CODES

3.1 MPACT v1.0

The MPACT (Michigan PArallel Charactistics based Transport) code being developed by the University of Michigan (UM) is designed to perform high-fidelity Light Water Reactor (LWR) analysis using whole-core transport calculations with neutron flux information provided at the sub-pin level. The code consists of several libraries which provide the functionality necessary to solve steady-state eigenvalue and power distribution problems. Several transport capabilities are available within MPACT including both 2D and 3D Method of Characteristics (MOC). References 1 and 3 provide the detailed description of MPACT and its capabilities as of version 0.2. Reference 2 documented the update to version 1.0 which included, among other items, CMFD acceleration for 2D lattice problems and support for the ORNL 60 group sub-group library, described below.

The available cross section libraries and methodologies used in this analysis are the following:

1. The ENDF/B-VI.8-based HELIOS 47-group cross section library with sub-group treatment. This library has been used extensively with DeCART (Ref. 10) and shown to produce good results relative to other ENDF/B-VI references. This library is not available through CASL (but is available to UM and ORNL) and is only used here to isolate effects from cross section sets and transport methods. The “unadjusted” library (i.e. unmodified U-238 resonance integral) is used for consistency with the CE KENO-VI libraries.

2. The ENDF/B-VII.0 ORNL 60 group cross section library (Ref. 9). This library has been developed by ORNL using the SCALE AMPX code system (Ref. 11) in order to provide CASL a releasable cross section capability. This library can be used with both sub-group and Embedded Self-Shielding (ESSM) cross section methodologies (Ref. 21). The sub-group data was added by ORNL for use with DeCART and MPACT. The ESSM data is provided for future development and testing.

The majority of MPACT results provided in this report are sub-group library based. The input for MPACT is as described in the User’s Manual (Ref. 3) and a samples are included in Appendices B and C. The common ASCII input being developed by CASL for VERA was not available for this analysis.

All of the MPACT calculations were performed on CASL’s Fissile Four cluster, on either U233, Pu239, or Pu241. These are x86 64 bit computers running Linux version 2.6.32-71.el6.x86_64. Each machine has 32 2000 MHz CPUs and 64 GB of memory (Ref. 23).

3.2 KENO-VI

KENO-VI, a functional module in the SCALE (Ref. 11) system, is a Monte Carlo criticality program used to calculate the reactivity of 3D systems (Ref. 5). The CSAS6 SCALE sequence performs the material and continuous energy (CE) cross section processing required for the particle transport. KENO-VI was selected for the lattice physics problems in this document because:

- The Monte Carlo approach to particle transport has no geometric approximations like deterministic solution techniques that use spatial discretization approaches.
- The use of Continuous Energy transport and cross sections are more rigorous than self-shielding cross section methods and multi-group treatments.
- The new KENO-VI parallel version permits simulations with an extremely large number of particles histories.
- Input for more complicated lattice geometry and multi-assembly cases is possible
- Association with SCALE and ORNL, including familiarity of analysts.

The SCALE Generalized Geometry Package permits construction of the models used in this document and in Reference 4 by combining geometric shapes such as cylinders and cuboids. For larger models, this input can become complicated, but automation programs have been developed for assistance. In this report, the KENO models were all constructed using quadrant symmetry to decrease the computer resources required to solve these problems and reduce the calculated reaction rate statistical uncertainties.

In addition to reactivity, KENO-VI can also provide reaction rate tallies by region, allowing the user, with some post-processing challenges, to extract the normalized fission reaction rate distribution for lattice physics problems. For this analysis, credit is taken for octant symmetry when possible, effectively doubling the sampling for symmetric rods and reducing the Monte Carlo estimated uncertainty for their fission rate. To reduce the uncertainty in the fission rates of individual fuel rods, especially lower powered ones, an extremely large number of particles is required. The uncertainties in the eigenvalues and power distributions obtained for the reference results are provided in Reference 4 and in the results below.

The KENO-VI version used for this analysis is a development version to be released in SCALE 6.2. The development version was utilized to take advantage of several new features and bug fixes, the most important to this effort being parallelization of the particle transport.

Both ENDF/B-VI.8 and ENDF/B-VII.0 CE cross section libraries were used to provide a corresponding reference solution. The ENDF/B-VII cross sections are the latest cross sections sets and are targeted for release with CASL. The KENO results with ENDF/B-VI.8 cross sections sets are being used for comparison with the MPACT results using the B-VI.8 HELIOS cross sections and the PARAGON ENDF/B-VI.3 results (with some limitations due to the different library version adopted, i.e. B-VI.3 vs. B-VI.8) . There are no ad-hoc adjustments made to the ENDF/B-VI.8 cross section data used by KENO-VI.

For more details on generation of the reference solutions for this analysis, see Reference 4. For the KENO results, 2500 generations where used with 400,000 particles per generation, skipping 250 generations. This resulted in an uncertainty in eigenvalue of less than 3 pcm.

3.3 MCNP5

MCNP5 is a general-purpose Monte Carlo N–Particle code that can be used for neutron, photon, electron, or coupled neutron/photon/electron transport, including the capability to calculate eigenvalues for critical systems (Ref. 6). Since a new KENO development (and patched) version is being utilized in this analysis, use of MCNP provides additional confidence of the accuracy of the reference solutions provided in Reference 4 and the degree of variability which may arise also in Monte-Carlo based solutions.

Only the ENDF/B-VII.0 continuous energy data libraries were used in the MCNP analysis. As with KENO, an extremely large number of particle histories were used to minimize the standard deviation of the fuel rod reaction rates. In this case, 2000 cycles were used with 50,000 particles per cycle, and 100 cycles were skipped. This resulted in an uncertainty in the eigenvalue of less than 7 pcm.

3.4 PARAGON

PARAGON is Westinghouse's state-of-the-art 2D lattice transport code. It is part of Westinghouse's reactor core design package and provides lattice cell data for three-dimensional (3D) core simulator codes (Ref. 7). These data include macroscopic cross sections, microscopic cross sections for feedback adjustments, pin factors for pin power reconstruction calculations, and discontinuity factors for the 3D advanced nodal code ANC (Refs. 18 and 20). PARAGON uses collision probability (CP) theory with the interface current cell coupling method to solve the integral transport equation. Throughout the entire calculation, PARAGON uses the exact heterogeneous geometry of the assembly and the same energy groups as in the cross section library to compute the multi-group fluxes for each micro-region location of the assembly. In order to generate the multi-group data, PARAGON goes through four steps of calculations: resonance self-shielding, flux solution, burnup calculation, and homogenization.

The 70-group PARAGON cross-section library used for production calculations is based on the ENDF/B-VI.3 basic nuclear data. This library has an extensive validation basis and it has been applied for design and analysis of commercial PWR cores for several years. A 70-group ENDF/B-VII.0 based library is also available (Refs. 13-14) and has been employed for this benchmark. Both B VI.3 and B VII.0-based libraries implement a reduction in the U-238 resonance integral as recommended in Reference 12 and discussed in Ref. 14. The ENDF/B-VII library includes an increase in the upper bound for the upscattering effects from 2.1eV to 4.0 eV to improve MOX fuel predictions, while showing similar overall accuracy for UO_2 core calculations, as discussed in Reference 15. In addition to the standard 70 group structure library, a prototypical ultra-fine library with over 6,000 energy groups ("6K") has been developed for PARAGON (Ref. 16) and employed for the comparisons given in this report. Due to the ultra-fine energy structure this library bypasses the approximations of the resonance self-shielding methodology altogether in the deterministic transport calculations and does not require adjustment of the U-238 resonance integral.

The 70-group PARAGON library includes explicit multi-group cross sections and other nuclear data for 174 isotopes, without any lumped fission products or pseudo cross sections. PARAGON and its 70-group cross section library are benchmarked, qualified, and approved both as a standalone transport code (Ref. 17) and as a nuclear data source for a core simulator in a complete nuclear design code system for core design, safety, and operational calculations (Ref. 18). Reference 17 addresses the qualification of the basic methodology used in PARAGON within a nuclear design system. The basic methodology and its implementation in PARAGON have been qualified through

comparisons to critical experiments and isotopic measurements. These include the Strawbridge experiments with Urania-Gadolinia fuel. Additionally, reactivity and power distribution comparisons between PARAGON and Monte Carlo (MCNP, Ref. 6) calculations for single assembly problems have been performed. Various assembly designs similar to those currently in use in PWR cores have been included in these comparisons. Isotopic comparisons have been made between PARAGON and the Yankee and Saxton isotopic measurements. Multi-assembly and up to full-core calculations can be performed as described in Reference 19. Calculations using PARAGON and 3D core simulator models have been compared against actual plant measurements, including boron letdown curves, beginning-of-cycle (BOC) hot-zero-power (HZP) critical boron concentrations, isothermal temperature coefficients, and control rod worths (Ref. 20). All these comparisons illustrate the accuracy of the PARAGON nuclear data in predicting core reactivity.

[

]

4. RESULTS

4.1 Single Assembly Lattices

The lattice physics problems used to test the performance of MPACT v1.0 are described in detail in Reference 4. They consist of typical 17x17 Westinghouse lattices with standard fuel pellets, representative of the fuel employed in TVA's Watts Bar Unit 1 Cycle 1 startup core. These cases are not meant to be an encompassing benchmark of a wide range of PWR conditions, but provide an opportunity for MPACT to demonstrate the current capabilities and to facilitate user feedback. These cases encapsulate Problem 2 in the AMA Core Physics Benchmark Progression Problems (Ref. 4), which focuses on the ability to accurately calculate the eigenvalue and pin power distribution of 2D lattice configurations.

For each lattice, calculations were performed for the following codes and cross sections:

1. ENDF/B-VII.0
    a. CE KENO-VI (from Reference 4)
    b. CE MCNP5
    c. MPACT v1.0 with ORNL 60 group sub-group library
    d. PARAGON with 70 group structure
    e. PARAGON with 6K (6064) group structure

2. ENDF/B-VI
    a. CE KENO-VI (from Reference 4) with ENDF/B-VI.8
    b. MPACT v1.0 with HELIOS 47 group using ENDF/B-VI.8
    c. PARAGON with 70 group structure using ENDF/B-VI.3
    d. PARAGON with 6K (6064) group structure using ENDF/B-VI.3

The executable and library files used for the MPACT v1.0 calculations were the following:

Executable / Filename	Date	Checksum
/home/bn7/mpact_bin/bin/MPACT_new.exe	12/3/2012 17:03	2541792733
/home/bn7/mpact_bin/data/hy047n18g110u.dat	9/18/2012 16:22	2236470032
/home/bn7/mpact_bin/data/declib60g02_e7.fmt	10/12/2012 18:29	863219409

For each result, eigenvalue differences are calculated between MPACT and the other codes, treating all of the other results as 'references'. These differences are reported in units of pcm according to the following formulation:

In addition, the normalized fission rate distributions (aka "pin powers") are compared using differences with units of percent:

For the pin power distributions, the maximum absolute difference and the Root Mean Square (RMS) of the population of differences are also calculated.

The following two tables describe the Problem 2 conditions, and Figure 2 shows the radial fuel and poison configurations for each lattice.

Table 1: Problem 2 Calculations
(Reference 4 – Table P2-1)

Problem	Description	Moderator Temperature†	Fuel Temperature	Moderator Density
2A	No Poisons	565 K	565 K	0.743 g/cc
2B	"	600 K	600 K	0.661 g/cc
2C	"	"	900 K	"
2D	"	"	1200 K	"
2E	12 Pyrex	"	600 K	0.743 g/cc
2F	24 Pyrex	"	"	"
2G	24 AIC	"	"	"
2H	24 B4C	"	"	"
2I	Instrument Thimble	"	"	"
2J	Instrument + 24 Pyrex	"	"	"
2K	Zoned + 24 Pyrex	"	"	"
2L	80 IFBA	"	"	"
2M	128 IFBA	"	"	"
2N	104 IFBA + 20 WABA	"	"	"
2O	12 Gadolinia	"	"	"
2P	24 Gadolinia	"	"	"

†Clad temperature set at moderator temperature

Table 2: Problem 2 Input Specification
(Reference 4 – Table P2-2)

General Input	Value
Nominal Fuel Density	10.257 g/cc
Nominal Fuel Enrichment	3.1%
Power	0% FP
Reactor Pressure	2250 psia
Boron Concentration	1300 ppm
2K Input (Zoned Enrichment)	
High Fuel Enrichment	3.6%
Low Fuel Enrichment	3.1%
2O and 2P Input (Gad Rods)	
Gadolinia Fuel Enrichment	1.8%
Gadolinia Fuel Density	10.111 g/cc

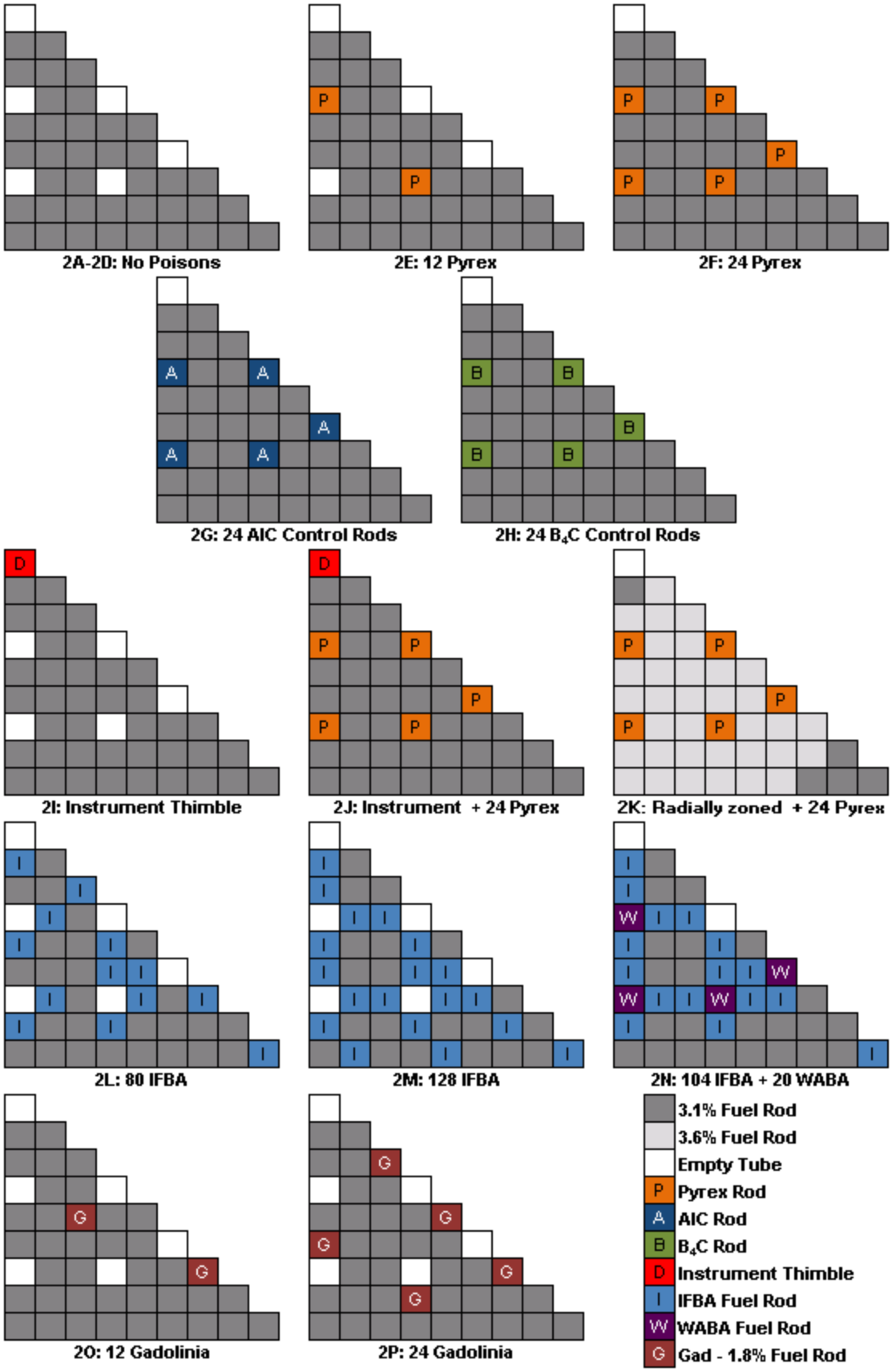


Figure 2: Problem 2 Lattice Layouts (Octant Symmetry)
(Reference 4 – Figure P2-2)

Tables 3 and 4 provide the eigenvalue results for all codes and cases. Figures 3 through 18 are the calculated pin power distributions from MPACT using the ORNL ENDF/B-VII 60 group cross section library. These results (including eigenvalue differences) will be discussed in the following sections of this report.

Table 3: Problem 2 ENDF/B-VII Eigenvalue Results

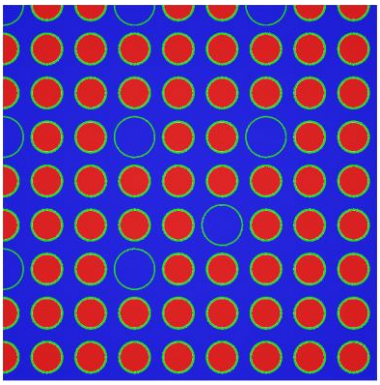
Problem	Description	KENO-VI CE	MCNP5 CE	PARAGON 6K	PARAGON 70g	MPACT 60g
2A	565K	1.18251	1.18154			1.18162
2B	600K	1.18403	1.18303			1.18263
2C	900K	1.17443	1.17378			1.17197
2D	1200K	1.16614	1.16598			1.16331
2E	12 Pyrex	1.07044	1.06915			1.06945
2F	24 Pyrex	0.97690	0.97529			0.97612
2G	24 AIC	0.84924	0.84682			0.85208
2H	24 B4C	0.78975	0.78723			0.79289
2I	Instrument Thimble	1.18056	1.17959			1.17921
2J	Instrument + 24 Pyrex	0.97610	0.97456			0.97537
2K	Zoned + 24 Pyrex	1.02100	1.01952			1.02017
2L	80 IFBA	1.01954	1.01844			1.01760
2M	128 IFBA	0.93946	0.93841			0.93741
2N	104 IFBA + 20 WABA	0.87043	0.86901			0.86820
2O	12 Gadolinia	1.04837	1.04735			1.04733
2P	24 Gadolinia	0.92800	0.92692			0.92799

KENO uncertainties are ≤ 3 pcm MCNP uncertainties are ≤ 7 pcm

Table 4: Problem 2 ENDF/B-VI Eigenvalue Results

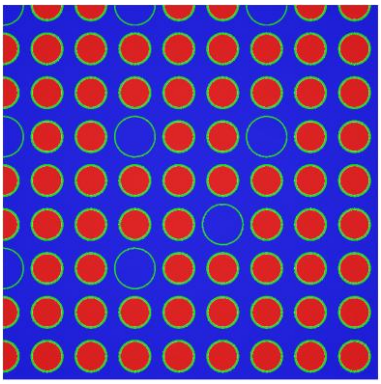
Problem	Description	KENO-VI CE	PARAGON 6K	PARAGON 70g	MPACT 47g
2A	565K	1.17828			1.17729
2B	600K	1.17977			1.17825
2C	900K	1.17031			1.16821
2D	1200K	1.16215			1.15978
2E	12 Pyrex	1.06660			1.06661
2F	24 Pyrex	0.97338			0.97416
2G	24 AIC	0.84563			0.85081
2H	24 B4C	0.78567			0.79056
2I	Instrument Thimble	1.17637			1.17509
2J	Instrument + 24 Pyrex	0.97262			0.97340
2K	Zoned + 24 Pyrex	1.01735			1.01776
2L	80 IFBA	1.01606			1.01503
2M	128 IFBA	0.93642			0.93529
2N	104 IFBA + 20 WABA	0.86773			0.86744
2O	12 Gadolinia	1.04575			1.04472
2P	24 Gadolinia	0.92664			0.92642

KENO uncertainties are ≤ 3 pcm



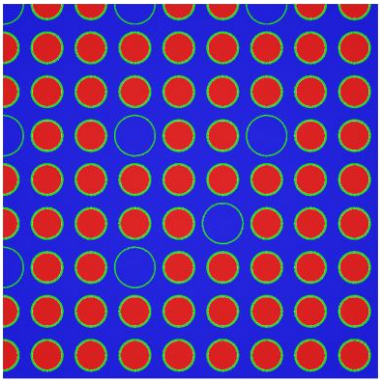
1.0348	1.0091							
1.0355	1.0092	1.0102						
	1.0354	1.0368						
1.0338	1.0086	1.0112	1.0437	1.0328				
1.0309	1.0055	1.0092	1.0438	1.0512				
	1.0255	1.0268		1.0363	1.0175	0.9747		
1.0113	0.9884	0.9887	1.0114	0.9845	0.9656	0.9494	0.9409	
0.9765	0.9726	0.9721	0.9742	0.9654	0.9563	0.9474	0.9436	0.9493

Figure 3: Problem 2A (565K) MPACT 60g Power Distribution Results



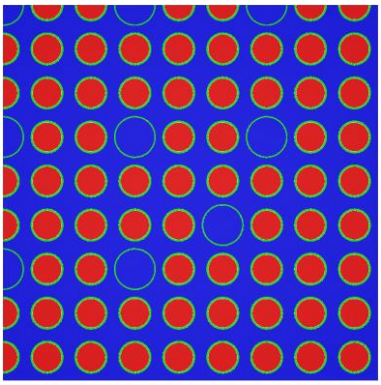
1.0344	1.0111							
1.0350	1.0110	1.0119						
	1.0346	1.0358						
1.0328	1.0100	1.0122	1.0416	1.0316				
1.0296	1.0066	1.0098	1.0410	1.0475				
	1.0239	1.0250		1.0330	1.0150	0.9750		
1.0104	0.9895	0.9896	1.0099	0.9848	0.9666	0.9509	0.9423	
0.9781	0.9745	0.9738	0.9753	0.9666	0.9576	0.9486	0.9445	0.9493

Figure 4: Problem 2B (600K) MPACT 60g Power Distribution Results



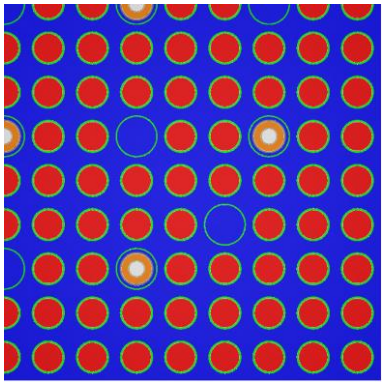
1.0345	1.0112							
1.0351	1.0111	1.0120						
	1.0347	1.0359						
1.0329	1.0100	1.0122	1.0416	1.0316				
1.0297	1.0066	1.0098	1.0410	1.0475				
	1.0240	1.0251		1.0330	1.0149	0.9750		
1.0104	0.9895	0.9896	1.0099	0.9847	0.9665	0.9508	0.9422	
0.9781	0.9745	0.9738	0.9753	0.9666	0.9575	0.9485	0.9444	0.9492

Figure 5: Problem 2C (900K) MPACT 60g Power Distribution Results



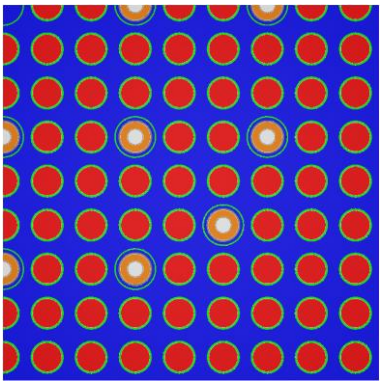
1.0346	1.0113							
1.0352	1.0112	1.0120						
	1.0348	1.0360						
1.0329	1.0100	1.0122	1.0417	1.0316				
1.0297	1.0066	1.0098	1.0410	1.0476				
	1.0240	1.0251		1.0330	1.0149	0.9749		
1.0105	0.9895	0.9896	1.0099	0.9847	0.9664	0.9507	0.9422	
0.9781	0.9745	0.9738	0.9752	0.9665	0.9574	0.9484	0.9443	0.9492

Figure 6: Problem 2D (1200K) MPACT 60g Power Distribution Results



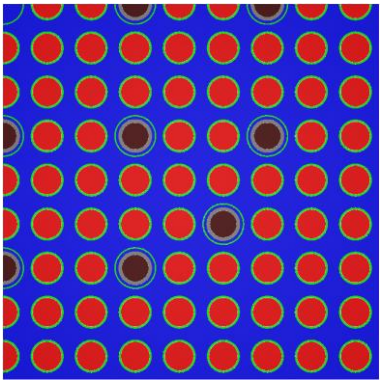
1.0167	0.9917							
0.9292	0.9618	0.9953						
	0.9319	1.0239						
0.9342	0.9674	1.0019	1.0364	1.0294				
1.0285	1.0025	0.9741	0.9515	1.0226				
	1.0352	0.9420		0.9591	1.0438	1.0330		
1.0580	1.0217	0.9759	0.9362	0.9789	1.0149	1.0255	1.0314	
1.0340	1.0231	1.0055	0.9945	1.0057	1.0224	1.0329	1.0414	1.0534

Figure 7: Problem 2E (12 Pyrex) MPACT 60g Power Distribution Results



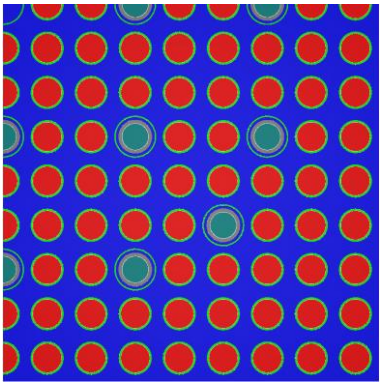
1.0748	1.0404							
0.9698	0.9880	0.9705						
	0.9323	0.9259						
0.9257	0.9572	0.9531	0.9125	0.9257				
0.9282	0.9600	0.9571	0.9141	0.9072				
	0.9427	0.9418		0.9360	0.9692	1.0345		
0.9740	1.0031	1.0047	0.9798	1.0194	1.0521	1.0838	1.1122	
1.0475	1.0527	1.0551	1.0562	1.0727	1.0932	1.1151	1.1354	1.1556

Figure 8: Problem 2F (24 Pyrex) MPACT 60g Power Distribution Results



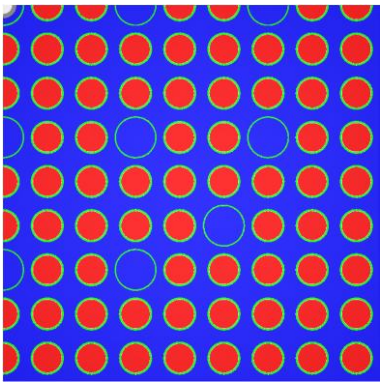
1.0704	1.0315							
0.9365	0.9614	0.9372						
	0.8849	0.8768						
0.8734	0.9175	0.9122	0.8561	0.8712				
0.8791	0.9243	0.9199	0.8595	0.8517				
	0.9096	0.9093		0.9081	0.9678	1.0719		
0.9647	1.0040	1.0082	0.9787	1.0391	1.0962	1.1529	1.2020	
1.0713	1.0791	1.0848	1.0908	1.1211	1.1599	1.2010	1.2369	1.2669

Figure 9: Problem 2G (AIC) MPACT 60g Power Distribution Results



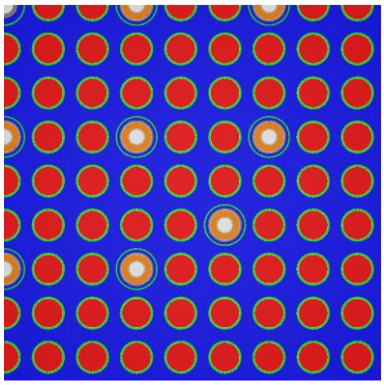
1.0582	1.0182							
0.9196	0.9441	0.9171						
	0.8644	0.8537						
0.8528	0.8973	0.8905	0.8320	0.8480				
0.8599	0.9065	0.9013	0.8390	0.8330				
	0.8981	0.8971		0.9024	0.9739	1.0918		
0.9617	1.0027	1.0081	0.9808	1.0491	1.1173	1.1852	1.2441	
1.0772	1.0858	1.0936	1.1037	1.1411	1.1895	1.2406	1.2849	1.3201

Figure 10: Problem 2H (B_4C) MPACT 60g Power Distribution Results



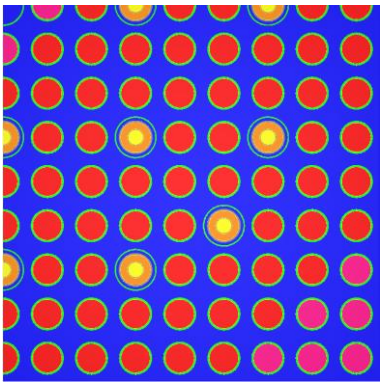
1.0028	0.9918							
1.0247	1.0021	1.0067						
	1.0323	1.0351						
1.0329	1.0087	1.0117	1.0439	1.0338				
1.0313	1.0067	1.0105	1.0445	1.0518				
	1.0265	1.0279		1.0372	1.0188	0.9769		
1.0127	0.9904	0.9907	1.0128	0.9865	0.9680	0.9520	0.9434	
0.9788	0.9750	0.9744	0.9765	0.9678	0.9588	0.9499	0.9461	0.9515

Figure 11: Problem 2I (Instrument Thimble) MPACT 60g Power Distribution Results



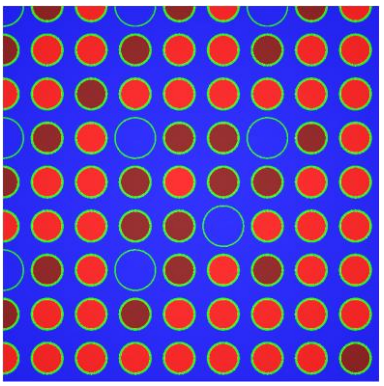
1.0385	1.0201							
0.9582	0.9797	0.9663						
	0.9298	0.9246						
0.9256	0.9571	0.9535	0.9134	0.9271				
0.9291	0.9610	0.9583	0.9155	0.9088				
	0.9442	0.9434		0.9378	0.9712	1.0367		
0.9758	1.0050	1.0067	0.9817	1.0215	1.0543	1.0862	1.1146	
1.0496	1.0548	1.0573	1.0584	1.0749	1.0956	1.1175	1.1379	1.1581

Figure 12: Problem 2J (Instrument and Pyrex) MPACT 60g Power Distribution Results



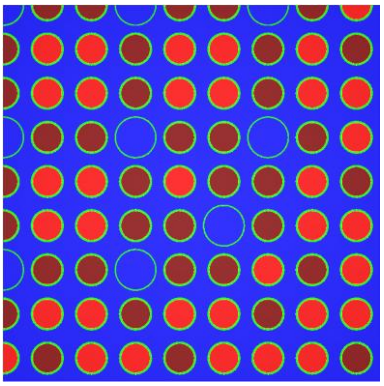
0.9746	1.0615							
0.9878	1.0023	0.9826						
	0.9452	0.9382						
0.9373	0.9673	0.9634	0.9246	0.9372				
0.9390	0.9692	0.9666	0.9262	0.9198				
	0.9522	0.9516		0.9479	0.9826	1.0506		
0.9815	1.0093	1.0112	0.9884	1.0287	1.0658	1.1081	1.0170	
1.0527	1.0576	1.0603	1.0629	1.0818	1.1108	1.0160	1.0460	1.0700

Figure 13: Problem 2K (Zoned and 24 Pyrex) MPACT 60g Power Distribution Results



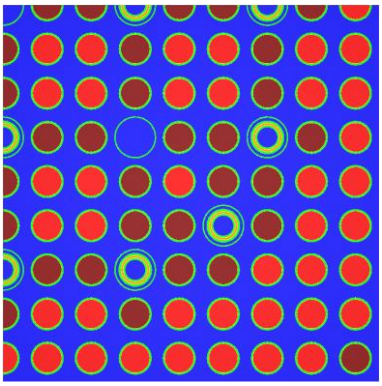
0.9455	0.9963							
1.0304	0.9993	0.9281						
	0.9522	1.0269						
0.9574	1.0093	1.0103	0.9387	0.9827				
1.0460	1.0221	1.0159	0.9379	0.9379				
	0.9669	1.0460		0.9533	1.0340	0.9396		
0.9630	1.0208	1.0284	0.9645	1.0172	1.0237	1.0118	1.0106	
1.0311	1.0368	1.0382	1.0316	1.0355	1.0376	1.0289	1.0054	0.9074

Figure 14: Problem 2L (80 IFBA) MPACT 60g Power Distribution Results



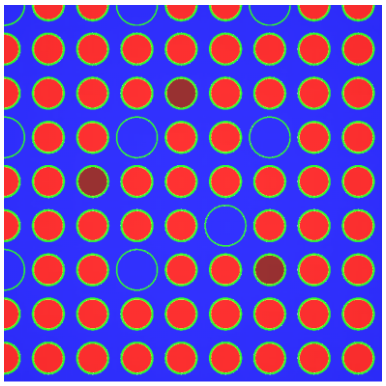
0.9809	1.0390							
0.9811	1.0388	1.0384						
	0.9805	0.9797						
0.9804	1.0377	1.0360	0.9742	1.0223				
0.9797	1.0363	1.0348	0.9691	0.9687				
	0.9754	0.9758		0.9692	0.9656	1.0067		
0.9711	1.0203	1.0312	0.9781	1.0195	1.0176	0.9451	1.0183	
1.0081	0.9428	1.0339	1.0301	0.9471	1.0343	1.0397	1.0333	0.9445

Figure 15: Problem 2M (128 IFBA) MPACT 60g Power Distribution Results



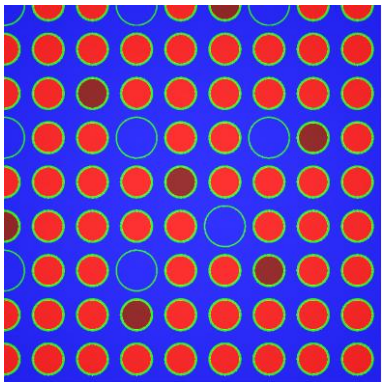
0.9716	1.0235							
0.8954	0.9926	1.0191						
	0.8885	0.9621						
0.8674	0.9696	1.0042	0.9446	0.9553				
0.8664	0.9623	0.9685	0.8640	0.8456				
	0.8810	0.8821		0.8703	0.9125	1.0582		
0.9238	1.0153	1.0178	0.9318	1.0378	1.0858	1.1314	1.1580	
1.0817	1.0929	1.0966	1.0946	1.1208	1.1498	1.1708	1.1649	1.0630

Figure 16: Problem 2N (104 IFBA + 20 WABA) MPACT 60g Power Distribution Results



1.1021	1.0693							
1.0863	1.0486	1.0186						
	1.0377	0.9791						
1.0468	0.9666	0.2154	0.9882	1.0388				
1.0709	1.0218	0.9789	1.0535	1.0810				
	1.0918	1.0823		1.0801	0.9942	0.2155		
1.1044	1.0784	1.0734	1.0922	1.0488	0.9926	0.9274	0.9647	
1.0774	1.0722	1.0679	1.0642	1.0435	1.0176	0.9950	1.0011	1.0183

Figure 17: Problem 2O (12 Gadolinia) MPACT 60g Power Distribution Results



1.1642	1.1091							
1.1398	1.0531	0.2415						
	1.1142	1.0632						
1.0660	1.0812	1.0884	1.0626	0.2416				
0.2429	1.0417	1.0958	1.1060	1.0621				
	1.1135	1.1057		1.0830	1.0384	0.2409		
1.1467	1.1094	1.0357	0.2416	1.0110	1.0412	1.0072	1.0615	
1.1321	1.1140	1.0632	0.9986	1.0440	1.0762	1.0841	1.1061	1.1317

Figure 18: Problem 2P (24 Gadolinia) MPACT 60g Power Distribution Results

Table 5 below provides the runtime performance of MPACT v1.0 with the HELIOS and ORNL subgroup libraries, as well as the ORNL library with ESSM. The runtime performance of HELIOS with the 47-group subgroup library is significantly better than that of MPACT with the 60-group subgroup library. It should be noted that a much smaller ray spacing is required for the IFBA cases, and use of the ORNL library requires a smaller spacing than use of the HELIOS library, which further degrades the runtime performance with IFBA fuel. The fine mesh ray tracing adopted for IFBA cases may impair the performance of MPACT over larger geometries with IFBA-bearing assemblies. Other differences such as the number of resonant isotopes, total number of energy groups, and number of upscattering groups may also account for some of the runtime differences between the two subgroup libraries. The runtime performance of MPACT with the ESSM library is significantly improved compared to the subgroup library.

The number of azimuthal angles per octant was 16 for all cases, the number of polar angles per octant was 2 for all cases, and the quadrature set used was Chebyshev-Yamamoto. A large series of mesh/ray refinement cases was performed to determine these optimal settings, but these results are not included in this document. Also, note that full symmetry is required due to current limitations in MPACT.

Table 5: MPACT Runtime Performance for Problem 2

		B-VI HELIOS 47g Sub-Group		B-VII ORNL 60g Sub-Group		B-VII ORNL 60g ESSM	
Case	**Cores**	**Ray Spacing (cm)**	**Time (mm:ss)**	**Ray Spacing (cm)**	**Time (mm:ss)**	**Ray Spacing (cm)**	**Time (mm:ss)**
2A	8	0.05	2:45	0.05	4:12	0.05	3:05
2B	8	0.05	2:46	0.05	4:11	0.05	3:00
2C	8	0.05	2:45	0.05	4:11	0.05	3:04
2D	8	0.05	2:47	0.05	4:26	0.05	3:04
2E	8	0.05	2:52	0.05	4:26	0.05	3:07
2F	8	0.05	2:53	0.05	4:26	0.05	3:11
2G	8	0.05	2:54	0.05	4:25	0.05	3:15
2H	8	0.05	2:48	0.05	4:35	0.05	3:11
2I	8	0.05	2:43	0.05	4:15	0.05	3:08
2J	8	0.05	2:50	0.05	4:24	0.05	3:17
2K	8	0.05	2:47	0.05	4:23	0.05	3:13
2L*	***8***	***0.01***	***9:12***	***0.004***	***32:00***	***0.004***	***22:21***
2M*	***8***	***0.01***	***9:21***	***0.004***	***35:50***	***0.004***	***22:33***
2N*	***8***	***0.01***	***9:27***	***0.004***	***33:42***	***0.004***	***23:17***
2O	8	0.05	2:56	0.05	4:23	0.05	3:38
2P	8	0.05	2:54	0.05	4:24	0.05	3:21

*IFBA cases

The runtime of PARAGON in 70 groups is less than 3 seconds per case, executed on a single processor with octant symmetry, which is significantly faster than MPACT.

Tables 6 and 7 on the following page display the eigenvalue differences (in pcm) and pin power differences (%) between MPACT and the other codes for each of the Problem 2 lattices. Figures 19-24 display this information in graphical form. Finally, the fission rate distribution differences between MPACT and the other codes are provided in Figures 25-40. Note that the approach taken is to provide a first validation of MPACT by comparing its results to each of the other codes used, e.g. KENO, MCNP and PARAGON, which already have a strong validation basis. The relative comparison between KENO, MCNP and PARAGON that can be inferred from these results should not be taken as indicative of the codes relative accuracy due to the limited scope of this benchmark problem and lack of any supporting experimental data.

Table 6: MPACT Differences with ORNL ENDF/B-VII 60g Library

		MPACT Eigenvalue Differences (pcm)				MPACT Pin Power RMS Diffs (%)				MPACT Pin Power Max Abs Diffs (%)			
Case	**Description**	**KENO CE**	**MCNP CE**	**PRGN 6K**	**PRGN 70g**	**KENO CE**	**MCNP CE**	**PRGN 6K**	**PRGN 70g**	**KENO CE**	**MCNP CE**	**PRGN 6K**	**PRGN 70g**
2A	565K	-88	9			0.09	0.09			0.22	0.24		
2B	600K	-140	-40			0.09	0.09			0.19	0.24		
2C	900K	-247	-181			0.08	0.09			0.18	0.27		
2D	1200K	-283	-267			0.09	0.08			0.21	0.20		
2E	12 Pyrex	-100	30			0.09	0.08			0.20	0.19		
2F	24 Pyrex	-79	83			0.14	0.16			0.31	0.33		
2G	24 AIC	284	**526**			0.20	0.21			0.47	0.47		
2H	24 B4C	**315**	**566**			0.23	0.19			0.49	0.40		
2I	Instrument Thimble	-135	-38			0.10	0.13			0.24	0.32		
2J	Instrument + 24 Pyrex	-73	81			0.15	0.13			0.33	0.35		
2K	Zoned + 24 Pyrex	-83	65			0.13	0.13			0.30	0.31		
2L	80 IFBA	-194	-84			0.17	0.17			0.37	0.40		
2M	128 IFBA	-205	-100			0.17	0.19			0.34	0.38		
2N	104 IFBA + 20 WABA	-223	-81			0.25	0.24			0.43	0.52		
2O	12 Gadolinia	-104	-2			0.15	0.13			0.37	0.28		
2P	24 Gadolinia	-1	107			0.18	0.18			0.40	0.49		

*PRGN = PARAGON

The estimated uncertainty in the KENO-VI pin powers is < 0.06%

In Tables 6 and 7, eigenvalue differences above 300 pcm are bold, as well as RMS pin power differences greater than 0.5% and maximum absolute pin power differences greater than 1%. Below are some summary observations on the data.

- MPACT compares very well to KENO and MCNP for all cases other than the controlled cases 2G and 2H. However, differences of 500-600 pcm are inconsequential for controlled lattices, which are well subcritical and not representative of actual core rodded configurations (i.e. finite array of checkerboard controlled assemblies vs. infinite array of controlled assemblies). This assertion is corroborated by the analysis of the 2D 3x3 assembly configuration with central rodded assembly, discussed further on in this report.
- There is an undesirable trend of increasing discrepancy in reactivity with increasing fuel temperature between MPACT and BOTH CE codes. [ ]
- MPACT compares very well to the reactivities calculated by PARAGON. [ ]
- The average difference between MPACT vs. KENO and MCNP for the HZP (600K) cases is ~-60 pcm with a standard deviation of ~90 pcm, excluding the rodded cases from the comparison. At a ~8 pcm/ppm soluble boron worth, this would translate into a -7 ± 12 ppm difference in the HZP start-up critical boron prediction, which is a good agreement. [ ]
- The differences observed between KENO and MCNP results are likely attributable to differences in library processing approaches (such as different thermal scattering cut off).

Table 7: MPACT Differences with HELIOS ENDF/B-VI 47g Library

		MPACT Eigenvalue Differences (pcm)			MPACT Pin Power RMS Diffs (%)			MPACT Pin Power Max Abs Diffs (%)		
Case	**Description**	**KENO CE**	**PARAGON 6K**	**PARAGON 70g**	**KENO CE**	**PARAGON 6K**	**PARAGON 70g**	**KENO CE**	**PARAGON 6K**	**PARAGON 70g**
2A	565K	-99			0.08			0.21		
2B	600K	-152			0.08			0.17		
2C	900K	-210			0.08			0.18		
2D	1200K	-237			0.07			0.17		
2E	12 Pyrex	1			0.07			0.24		
2F	24 Pyrex	78			0.13			0.30		
2G	24 AIC	**519**			0.34			0.71		
2H	24 B4C	**489**			0.33			0.71		
2I	Instrument Thimble	-128			0.08			0.18		
2J	Instrument + 24 Pyrex	79			0.13			0.31		
2K	Zoned + 24 Pyrex	41			0.13			0.25		
2L	80 IFBA	-103			0.09			0.24		
2M	128 IFBA	-113			0.10			0.22		
2N	104 IFBA + 20 WABA	-29			0.09			0.16		
2O	12 Gadolinia	-103			0.12			0.25		
2P	24 Gadolinia	-22			0.17			0.38		

- In addition to the observations from the ENDF-BVII comparison in Table 6, the differences with the ENDF/B-VI cross sections, reported in Table 7, are typically larger, likely due to the fact that different versions of the ENDF/B-VI library are used (i.e. BVI.3 for PARAGON and BVI.8 for the other codes).

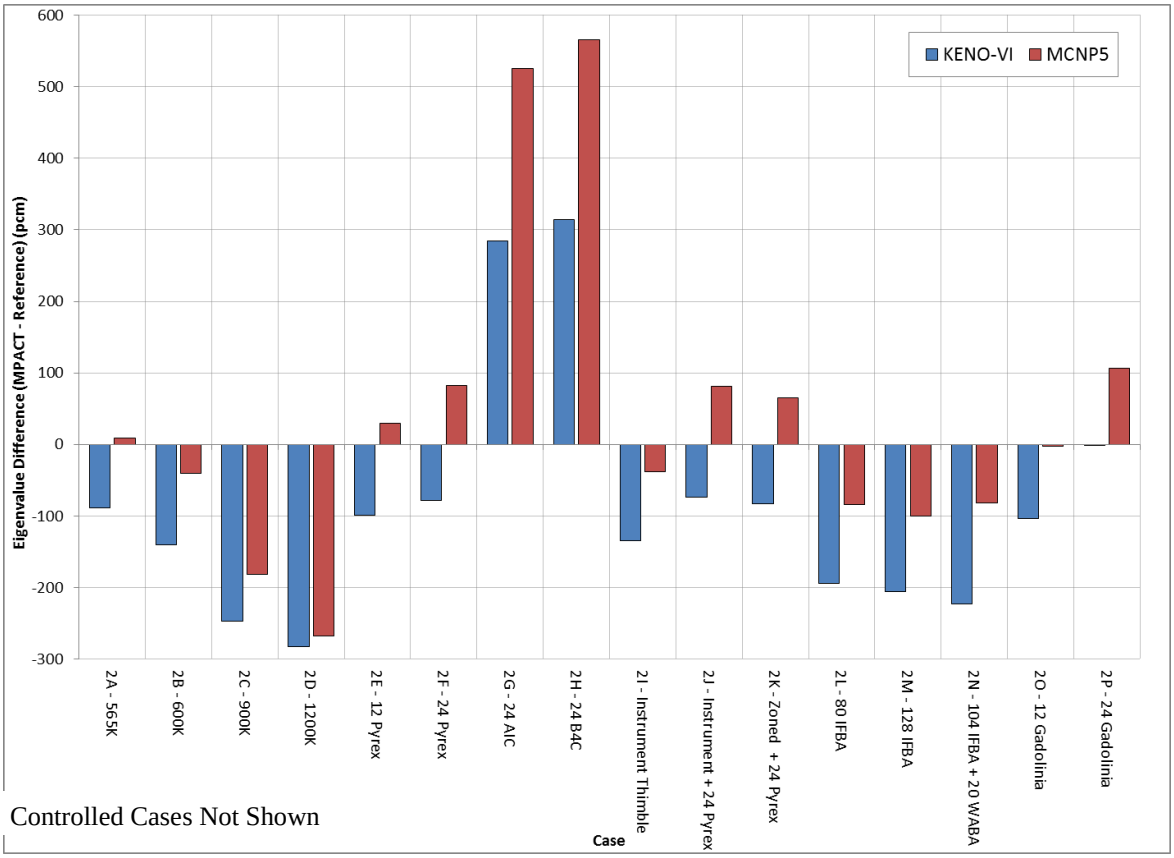


Figure 19: MPACT Eigenvalue Differences with B-VII Cross Sections

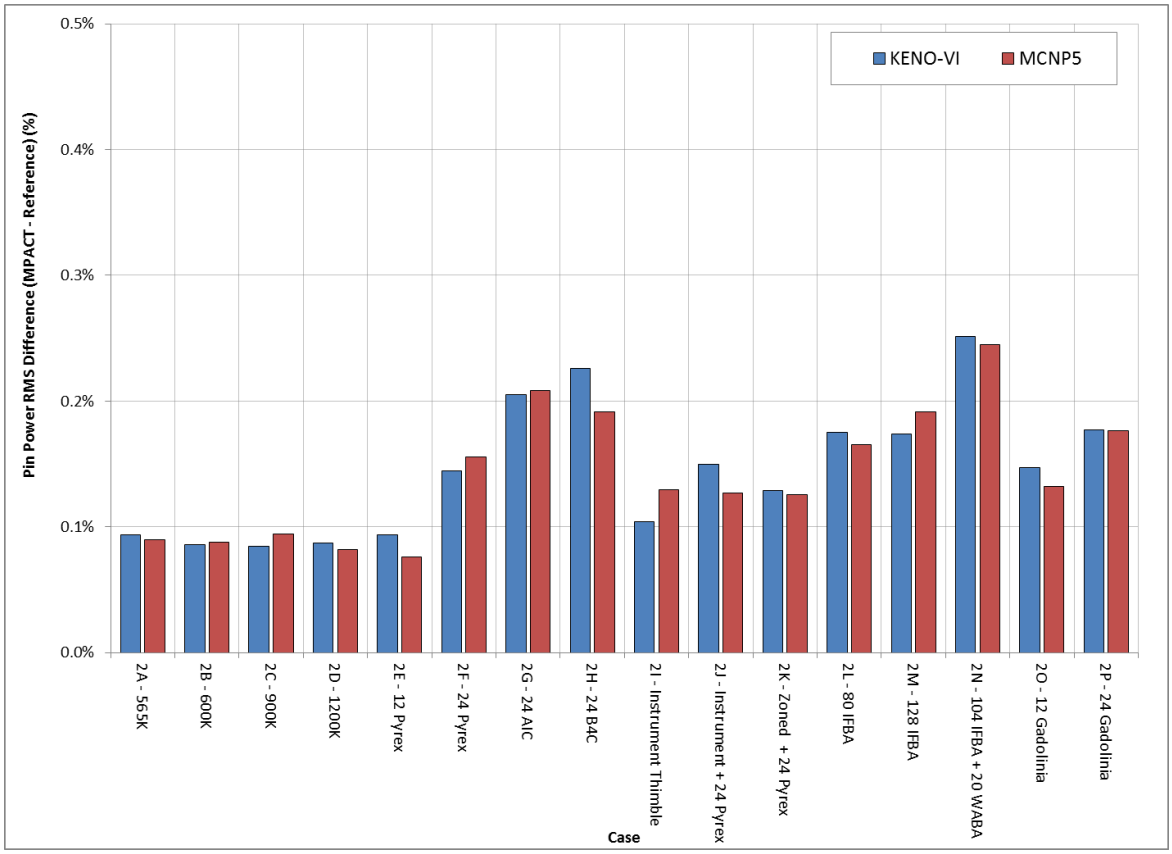


Figure 20: MPACT Pin Power RMS Differences with B-VII Cross Sections

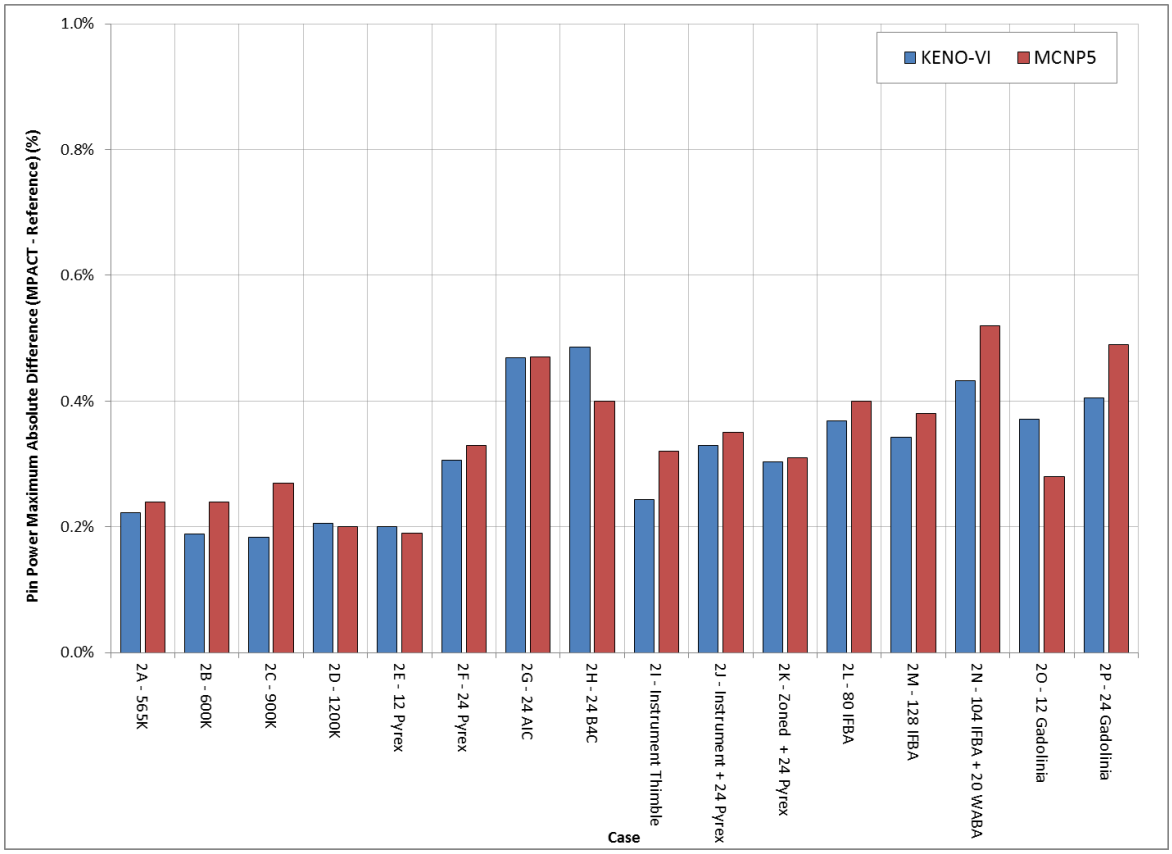


Figure 21: MPACT Maximum Absolute Pin Power Differences with B-VII Cross Sections

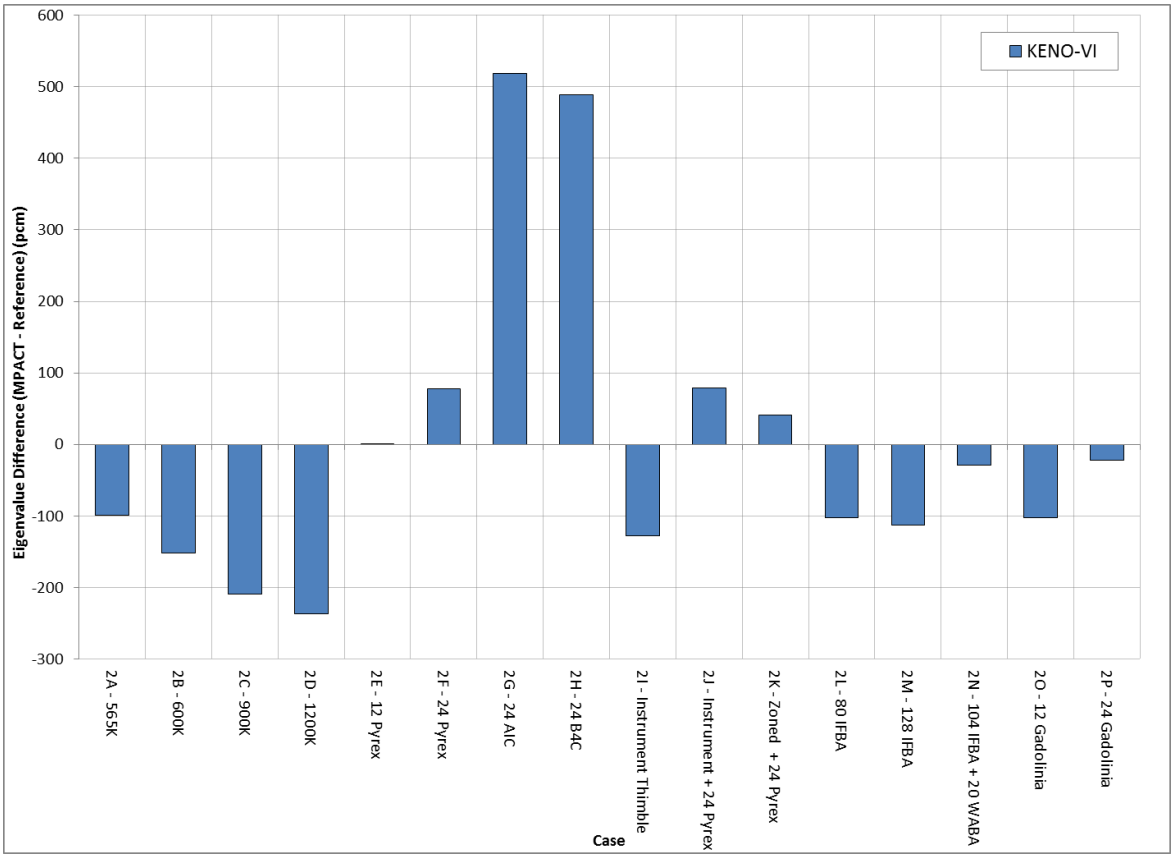


Figure 22: MPACT Eigenvalue Differences with B-VI Cross Sections

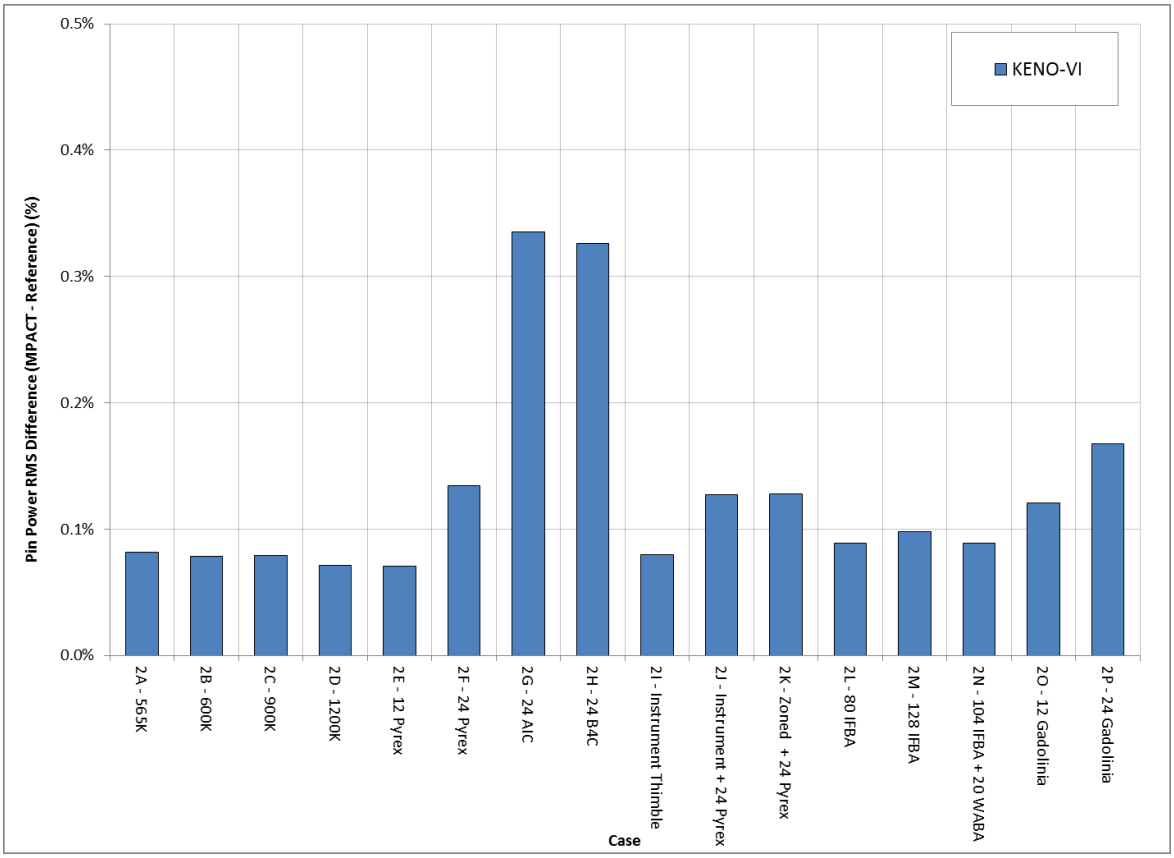


Figure 23: MPACT Pin Power RMS Differences with B-VI Cross Sections

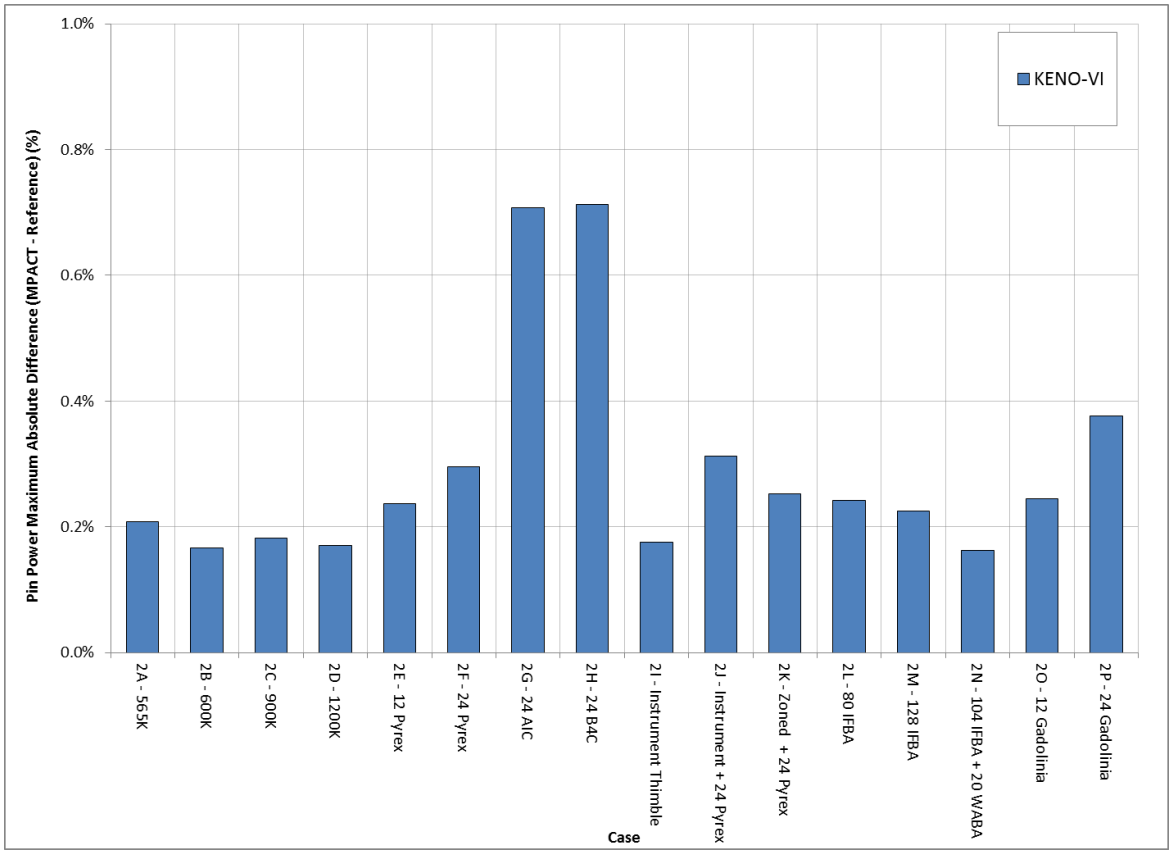


Figure 24: MPACT Maximum Absolute Pin Power Differences with B-VI Cross Sections

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI (adjusted to 565K)

-0.10	-0.03							
-0.10	-0.02	0.08						
	-0.22	-0.22						
-0.16	0.06	0.04	-0.18	0.03				
-0.09	-0.03	-0.02	-0.10	-0.01				
	-0.02	-0.10		0.02	0.05	0.07		
-0.03	0.06	-0.01	-0.02	0.11	0.06	0.06	0.15	
0.03	0.07	0.02	0.05	0.07	0.14	0.12	0.10	0.05

Max: 0.15 Min: -0.22 RMS: 0.09

MCNP5 (at 600K)

-0.06	-0.08							
-0.10	-0.06	-0.06						
	-0.11	-0.19						
-0.10	-0.07	0.05	-0.06	0.13				
-0.10	-0.10	0.06	-0.04	0.16				
	-0.05	-0.07		0.13	0.04	0.09		
-0.03	0.03	0.00	0.02	0.12	0.01	0.03	0.15	
-0.10	-0.01	-0.01	-0.06	-0.08	0.05	0.11	0.13	0.24

Max: 0.24 Min: -0.19 RMS: 0.09

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI (adjusted to 565K)

-0.09	0.10							
-0.02	-0.01	0.12						
	-0.15	-0.19						
-0.13	0.10	0.02	-0.21	0.06				
-0.14	-0.04	0.02	-0.05	0.01				
	-0.01	-0.09		-0.02	0.03	0.03		
0.00	0.03	0.03	-0.04	0.12	-0.02	0.00	0.07	
0.02	0.07	0.05	0.03	0.05	0.12	0.06	0.08	-0.01

Max: 0.12 Min: -0.21 RMS: 0.08

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 25: MPACT Problem 2A Power Distribution Comparisons

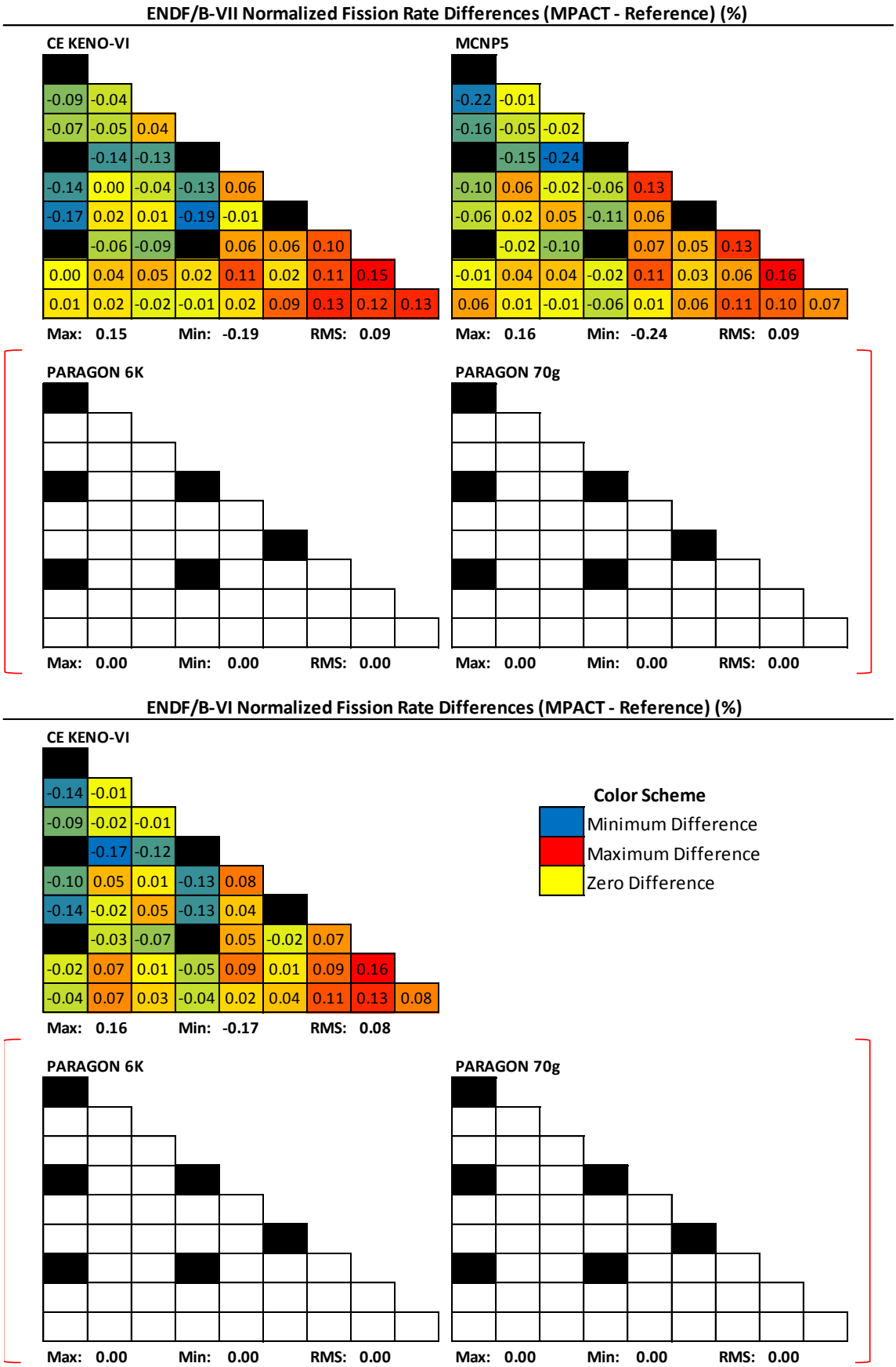


Figure 26: MPACT Problem 2B Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.13	0.01							
-0.11	-0.03	-0.05						
	-0.18	-0.14						
-0.11	0.00	-0.03	-0.11	0.09				
-0.14	-0.01	0.02	-0.14	0.01				
	-0.05	-0.05		0.01	0.02	0.10		
-0.03	0.06	0.07	-0.01	0.09	0.05	0.05	0.17	
0.01	0.01	0.05	-0.01	-0.01	0.06	0.14	0.17	0.14

Max: 0.17 Min: -0.18 RMS: 0.08

MCNP5

-0.14	-0.09							
-0.10	-0.05	-0.02						
	-0.06	-0.13						
-0.17	-0.06	-0.02	-0.10	0.06				
-0.11	-0.04	0.05	-0.13	0.02				
	-0.07	-0.08		-0.06	-0.03	0.14		
0.05	0.08	0.02	0.01	0.04	0.06	0.13	0.27	
-0.09	-0.04	-0.02	0.00	0.02	0.09	0.15	0.19	0.23

Max: 0.27 Min: -0.17 RMS: 0.09

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.10	0.05							
-0.09	0.01	0.05						
	-0.13	-0.15						
-0.17	0.02	0.06	-0.11	0.11				
-0.18	-0.04	0.03	-0.14	-0.02				
	-0.02	-0.09		0.05	-0.01	0.06		
-0.01	0.03	0.04	-0.03	0.11	0.02	0.04	0.11	
0.00	0.01	0.04	-0.01	0.04	0.05	0.09	0.12	0.17

Max: 0.17 Min: -0.18 RMS: 0.08

Color Scheme

- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 27: MPACT Problem 2C Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.21	-0.04							
-0.07	-0.05	-0.05						
	-0.19	-0.14						
-0.12	0.05	-0.03	-0.12	0.08				
-0.18	0.00	0.03	-0.11	0.03				
	-0.06	-0.09		0.00	0.02	0.13		
-0.01	0.05	0.06	-0.04	0.08	0.05	0.09	0.15	
-0.03	0.05	0.02	0.01	0.09	0.10	0.08	0.14	0.12

Max: 0.15 Min: -0.21 RMS: 0.09

MCNP5

-0.02	0.06							
-0.08	0.07	0.05						
	-0.10	-0.17						
-0.10	-0.02	-0.02	-0.10	0.07				
-0.19	-0.01	-0.06	-0.14	0.06				
	-0.04	-0.05		0.06	0.00	0.10		
-0.04	0.05	0.08	-0.03	0.09	0.03	0.09	0.20	
-0.01	-0.06	-0.09	0.02	-0.03	0.06	0.10	0.07	0.18

Max: 0.20 Min: -0.19 RMS: 0.08

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.09	0.08							
-0.07	-0.01	-0.01						
	-0.15	-0.11						
-0.05	0.00	0.00	-0.14	0.11				
-0.06	0.02	0.09	-0.17	0.01				
	-0.09	-0.09		0.05	0.01	0.03		
-0.02	0.05	0.02	-0.02	0.08	-0.01	0.09	0.10	
0.01	0.05	0.01	0.00	0.04	0.03	0.07	0.07	0.08

Max: 0.11 Min: -0.17 RMS: 0.07

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 28: MPACT Problem 2D Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.08	-0.06							
-0.04	-0.14	-0.10						
	-0.05	-0.11						
-0.10	-0.18	-0.08	-0.06	0.12				
0.03	-0.06	-0.07	-0.01	-0.05				
	-0.02	-0.04		0.11	0.08	0.08		
-0.06	-0.02	-0.09	0.14	0.01	0.06	0.17	0.16	
-0.10	-0.04	-0.04	0.06	0.02	0.13	0.11	0.16	0.20

Max: 0.20 Min: -0.18 RMS: 0.09

MCNP5

-0.04	-0.04							
-0.04	-0.19	-0.01						
	-0.06	-0.09						
-0.06	-0.09	-0.06	-0.08	-0.04				
0.06	-0.03	0.02	0.00	-0.06				
	0.04	-0.07		0.11	0.05	0.06		
-0.09	-0.02	-0.03	0.09	0.03	0.01	0.09	0.08	
-0.09	-0.04	0.01	0.08	-0.01	0.12	0.13	0.07	0.18

Max: 0.18 Min: -0.19 RMS: 0.08

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.01	0.06							
0.06	-0.08	-0.01						
	0.11	-0.01						
0.04	-0.08	0.02	0.01	0.15				
0.00	-0.06	-0.08	0.01	-0.07				
	0.01	0.04		0.24	0.04	0.10		
-0.10	-0.04	-0.04	0.12	-0.04	-0.04	-0.03	0.01	
-0.12	-0.01	-0.02	0.05	-0.01	-0.04	-0.02	-0.08	-0.05

Max: 0.24 Min: -0.12 RMS: 0.07

Color Scheme

- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 29: MPACT Problem 2E Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.21	-0.14							
-0.20	-0.31	-0.31						
	-0.10	-0.04						
-0.06	-0.19	-0.16	0.07	-0.06				
0.02	-0.17	-0.16	0.14	0.02				
	0.07	0.06		0.05	0.22	0.05		
-0.09	-0.15	-0.12	0.10	0.03	0.19	0.17	0.30	
-0.09	-0.05	-0.03	0.08	0.07	0.15	0.19	0.16	0.17

Max: 0.30 Min: -0.31 RMS: 0.14

MCNP5

-0.33	-0.32							
-0.23	-0.33	-0.28						
	-0.10	0.04						
-0.03	-0.18	-0.15	0.09	-0.12				
0.02	-0.10	-0.15	0.18	0.03				
	0.10	0.08		0.04	0.29	0.06		
-0.01	-0.20	-0.11	0.12	0.07	0.19	0.10	0.21	
-0.13	-0.11	-0.04	0.05	0.12	0.10	0.13	0.16	0.27

Max: 0.29 Min: -0.33 RMS: 0.16

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.19	-0.06							
0.05	-0.13	-0.14						
	0.07	0.08						
0.18	-0.09	-0.01	0.24	-0.02				
0.14	-0.10	-0.04	0.30	0.19				
	0.23	0.17		0.09	0.24	-0.02		
0.01	-0.18	-0.12	0.06	-0.06	0.03	-0.11	-0.11	
-0.15	-0.12	-0.12	-0.04	-0.03	-0.10	-0.08	-0.08	-0.19

Max: 0.30 Min: -0.19 RMS: 0.13

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 30: MPACT Problem 2F Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.38	-0.39							
-0.30	-0.47	-0.40						
	-0.06	0.01						
-0.01	-0.28	-0.26	0.25	-0.12				
0.02	-0.26	-0.16	0.35	0.06				
	0.07	0.16		0.14	0.30	0.12		
0.03	-0.21	-0.10	0.09	0.02	0.13	0.11	0.33	
0.06	-0.12	-0.10	0.15	0.10	0.20	0.13	0.19	0.16

Max: 0.35 Min: -0.47 RMS: 0.20

MCNP5

-0.46	-0.41							
-0.36	-0.47	-0.37						
	-0.01	0.04						
0.13	-0.20	-0.11	0.37	-0.01				
0.03	-0.22	-0.07	0.44	0.14				
	0.17	0.21		0.20	0.29	0.04		
0.13	-0.24	-0.23	0.11	0.01	0.12	0.09	0.14	
0.04	-0.14	-0.14	0.05	-0.04	0.10	0.06	-0.02	0.04

Max: 0.44 Min: -0.47 RMS: 0.21

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.24	-0.33							
-0.04	-0.20	-0.09						
	0.31	0.41						
0.38	-0.01	0.11	0.62	0.22				
0.39	-0.02	0.13	0.67	0.41				
	0.39	0.40		0.25	0.30	-0.20		
0.12	-0.20	-0.15	0.10	-0.11	-0.08	-0.44	-0.41	
-0.04	-0.24	-0.32	-0.13	-0.28	-0.33	-0.51	-0.61	-0.71

Max: 0.67 Min: -0.71 RMS: 0.34

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 31: MPACT Problem 2G Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.25	-0.32							
-0.27	-0.46	-0.49						
	-0.04	-0.13						
0.11	-0.27	-0.32	0.05	-0.33				
0.05	-0.28	-0.21	0.23	-0.15				
	0.18	0.09		-0.01	0.27	0.23		
0.05	-0.18	-0.19	0.02	-0.02	0.28	0.24	0.38	
0.12	-0.04	-0.03	0.23	0.11	0.23	0.30	0.33	0.27

Max: 0.38 Min: -0.49 RMS: 0.23

MCNP5

-0.28	-0.31							
-0.20	-0.40	-0.40						
	0.03	0.00						
0.25	-0.13	-0.23	0.12	-0.28				
0.21	-0.22	-0.13	0.37	-0.10				
	0.36	0.19		0.05	0.28	-0.02		
0.06	-0.19	-0.17	0.06	-0.05	0.10	0.08	0.19	
-0.05	-0.15	-0.05	0.21	0.05	0.19	0.10	0.04	-0.05

Max: 0.37 Min: -0.40 RMS: 0.19

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.01	-0.08							
0.06	-0.15	-0.10						
	0.41	0.39						
0.42	0.07	0.08	0.49	0.07				
0.44	0.03	0.08	0.64	0.23				
	0.46	0.38		0.16	0.28	-0.20		
0.13	-0.12	-0.19	0.05	-0.22	-0.11	-0.46	-0.44	
0.03	-0.16	-0.26	-0.03	-0.28	-0.33	-0.57	-0.68	-0.71

Max: 0.64 Min: -0.71 RMS: 0.33

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 32: MPACT Problem 2H Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.22	-0.05							
-0.09	-0.03	-0.01						
	-0.20	-0.21						
-0.21	0.01	-0.01	-0.16	0.10				
-0.15	-0.01	0.08	-0.13	-0.02				
	-0.05	-0.09		0.00	0.01	0.12		
-0.06	0.02	0.06	0.02	0.11	0.10	0.13	0.24	
-0.01	0.04	0.02	0.01	0.04	0.12	0.13	0.12	0.19

Max: 0.24 Min: -0.22 RMS: 0.10

MCNP5

-0.08	-0.07							
-0.19	-0.07	-0.05						
	-0.14	-0.32						
-0.08	0.00	-0.05	-0.21	0.07				
-0.27	-0.09	-0.03	-0.14	0.02				
	0.00	-0.08		0.03	0.00	0.12		
-0.07	0.03	0.01	0.01	0.24	0.08	0.16	0.20	
-0.07	0.07	0.00	0.01	0.10	0.15	0.10	0.26	0.27

Max: 0.27 Min: -0.32 RMS: 0.13

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.16	-0.07							
0.00	-0.01	0.05						
	-0.12	-0.16						
-0.06	0.02	-0.01	-0.09	0.14				
-0.13	-0.01	0.11	-0.15	-0.03				
	-0.07	-0.08		0.05	-0.05	0.09		
-0.03	0.00	0.07	-0.03	0.09	0.00	0.07	0.18	
0.02	0.08	0.02	-0.01	0.02	0.07	0.04	0.09	0.13

Max: 0.18 Min: -0.16 RMS: 0.08

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 33: MPACT Problem 2I Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.24	-0.33							
-0.12	-0.25	-0.28						
	-0.03	-0.07						
-0.05	-0.23	-0.24	0.04	-0.08				
0.03	-0.19	-0.11	0.16	0.06				
	0.05	0.06		0.07	0.21	0.02		
0.01	-0.13	-0.09	0.04	0.03	0.20	0.15	0.27	
-0.01	-0.06	-0.07	0.04	0.07	0.12	0.21	0.23	0.24

Max: 0.27 Min: -0.33 RMS: 0.15

MCNP5

-0.35	-0.21							
-0.08	-0.26	-0.17						
	-0.07	0.06						
-0.02	-0.21	-0.15	0.06	0.00				
0.05	-0.24	-0.05	0.18	0.06				
	0.09	0.10		0.11	0.20	0.06		
0.05	-0.12	-0.06	0.11	0.01	0.06	0.09	0.11	
0.10	-0.11	-0.06	0.11	-0.02	0.06	0.11	0.10	0.09

Max: 0.20 Min: -0.35 RMS: 0.13

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.17	-0.18							
-0.01	-0.19	-0.12						
	0.08	0.09						
0.14	-0.09	-0.01	0.22	-0.06				
0.16	-0.07	-0.09	0.31	0.19				
	0.17	0.12		0.12	0.22	0.02		
0.03	-0.08	-0.10	0.09	-0.03	-0.01	-0.06	-0.05	
-0.07	-0.08	-0.17	-0.04	-0.11	-0.05	-0.07	-0.14	-0.12

Max: 0.31 Min: -0.19 RMS: 0.13

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 34: MPACT Problem 2J Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.22	-0.12							
-0.16	-0.26	-0.30						
	-0.06	-0.05						
-0.02	-0.16	-0.21	0.09	-0.15				
0.03	-0.18	-0.14	0.13	0.03				
	0.09	0.07		0.08	0.20	0.05		
0.01	-0.14	-0.04	0.07	-0.01	0.15	0.10	0.21	
0.09	-0.05	-0.03	0.07	0.07	0.16	0.11	0.13	0.15

Max: 0.21 Min: -0.30 RMS: 0.13

MCNP5

-0.16	-0.26							
-0.18	-0.31	-0.20						
	-0.06	0.01						
0.02	-0.15	-0.12	0.10	-0.05				
0.01	-0.18	-0.14	0.23	0.05				
	0.11	0.10		0.03	0.23	0.03		
-0.08	-0.05	-0.06	0.08	0.03	0.17	-0.06	0.16	
0.01	-0.05	0.01	0.08	0.00	0.01	0.11	0.13	0.08

Max: 0.23 Min: -0.31 RMS: 0.13

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.08	-0.24							
-0.03	-0.17	-0.09						
	0.12	0.09						
0.15	-0.08	-0.06	0.21	-0.05				
0.13	-0.08	-0.02	0.25	0.18				
	0.19	0.15		0.15	0.19	-0.04		
0.08	-0.08	-0.10	0.14	-0.12	-0.04	-0.15	0.01	
-0.09	-0.06	-0.11	0.00	-0.08	-0.11	-0.11	-0.11	-0.17

Max: 0.25 Min: -0.24 RMS: 0.13

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 35: MPACT Problem 2K Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.28	-0.07							
-0.22	-0.10	-0.26						
	-0.37	-0.19						
-0.27	0.02	-0.05	-0.21	0.08				
-0.17	0.04	-0.04	-0.21	-0.12				
	-0.24	-0.05		-0.09	0.10	0.05		
-0.13	0.12	0.08	-0.06	0.18	0.07	0.23	0.27	
0.06	0.04	0.10	0.11	0.16	0.25	0.30	0.30	0.27

Max: 0.30 Min: -0.37 RMS: 0.17

MCNP5

-0.34	-0.04							
-0.22	-0.04	-0.26						
	-0.40	-0.18						
-0.24	-0.01	-0.04	-0.18	0.15				
-0.12	0.04	0.02	-0.23	-0.08				
	-0.20	-0.01		-0.05	0.05	-0.05		
-0.18	0.15	0.10	-0.07	0.24	0.14	0.17	0.26	
0.06	0.06	0.07	0.08	0.12	0.21	0.29	0.21	0.12

Max: 0.29 Min: -0.40 RMS: 0.17

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.09	0.10							
-0.08	0.04	-0.06						
	-0.18	-0.13						
-0.13	0.07	0.03	-0.08	0.24				
-0.08	0.03	0.03	-0.06	0.04				
	-0.14	-0.12		0.03	0.04	0.07		
-0.05	0.06	0.07	-0.04	0.16	-0.04	0.12	0.04	
0.01	-0.05	-0.01	-0.03	-0.03	-0.01	0.10	0.03	0.23

Max: 0.24 Min: -0.18 RMS: 0.09

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 36: MPACT Problem 2L Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.26	0.00							
-0.24	-0.02	-0.06						
	-0.30	-0.24						
-0.21	0.05	-0.03	-0.20	0.15				
-0.15	0.00	0.03	-0.21	-0.11				
	-0.26	-0.17		-0.06	-0.06	0.23		
-0.19	0.09	0.08	-0.08	0.24	0.14	0.13	0.30	
0.10	-0.06	0.04	0.11	0.01	0.21	0.34	0.34	0.29

Max: 0.34 Min: -0.30 RMS: 0.17

MCNP5

-0.28	-0.08							
-0.32	0.00	0.00						
	-0.32	-0.28						
-0.25	0.03	-0.07	-0.27	0.12				
-0.29	0.01	-0.04	-0.24	-0.12				
	-0.16	-0.19		-0.04	-0.05	0.22		
-0.25	0.10	0.13	-0.03	0.28	0.21	0.10	0.32	
0.08	0.00	0.16	0.09	0.04	0.29	0.38	0.30	0.14

Max: 0.38 Min: -0.32 RMS: 0.19

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.07	0.02							
-0.14	0.04	0.04						
	-0.14	-0.17						
-0.18	0.08	0.05	-0.13	0.22				
-0.16	0.05	0.04	-0.11	0.01				
	-0.16	-0.09		0.04	-0.04	0.13		
-0.12	0.15	0.08	-0.11	0.11	0.04	-0.01	0.11	
0.01	0.06	-0.01	-0.04	0.00	0.04	0.10	0.10	0.16

Max: 0.22 Min: -0.18 RMS: 0.10

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 37: MPACT Problem 2M Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.38	-0.33							
-0.43	-0.37	-0.28						
	-0.35	-0.39						
-0.25	-0.23	-0.15	-0.22	-0.03				
-0.09	-0.21	-0.13	-0.12	-0.08				
	-0.10	-0.06		0.02	0.16	0.29		
-0.10	-0.02	-0.07	0.03	0.16	0.34	0.38	0.43	
0.08	0.02	0.05	0.24	0.20	0.40	0.43	0.43	0.37

Max: 0.43 Min: -0.43 RMS: 0.25

MCNP5

-0.41	-0.29							
-0.49	-0.39	-0.18						
	-0.40	-0.37						
-0.18	-0.24	-0.15	-0.16	0.01				
-0.11	-0.15	-0.06	-0.06	-0.05				
	-0.02	-0.10		-0.08	0.15	0.31		
-0.14	-0.07	0.00	0.01	0.07	0.32	0.37	0.32	
0.08	0.01	0.03	0.24	0.17	0.38	0.41	0.52	0.26

Max: 0.52 Min: -0.49 RMS: 0.24

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.03	-0.10							
-0.15	-0.13	-0.07						
	-0.13	-0.14						
0.04	-0.12	-0.03	-0.05	0.11				
0.07	-0.06	0.02	0.12	0.10				
	0.12	0.11		0.13	0.16	0.15		
-0.03	-0.04	-0.07	0.02	0.08	0.08	-0.01	0.02	
-0.05	-0.10	-0.10	0.05	-0.03	-0.01	0.03	0.00	0.05

Max: 0.16 Min: -0.15 RMS: 0.09

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 38: MPACT Problem 2N Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.37	-0.11							
-0.20	-0.18	0.04						
	-0.37	-0.16						
-0.03	0.14	-0.14	0.02	0.19				
-0.31	-0.09	0.19	-0.22	-0.04				
	-0.10	-0.03		0.08	0.13	-0.12		
-0.06	0.11	0.02	0.03	0.17	0.01	0.21	0.11	
-0.07	0.10	0.04	0.04	0.01	0.11	0.21	0.13	0.09

Max: 0.21 Min: -0.37 RMS: 0.15

MCNP5

-0.27	-0.11							
-0.24	-0.19	0.06						
	-0.28	-0.13						
-0.19	0.12	-0.12	0.01	0.15				
-0.19	-0.10	0.19	-0.19	-0.05				
	-0.13	0.08		0.11	0.12	-0.05		
0.07	0.06	0.02	-0.03	0.08	-0.02	0.24	0.08	
-0.10	0.02	0.03	0.02	0.04	0.11	0.18	0.12	0.19

Max: 0.24 Min: -0.28 RMS: 0.13

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.19	-0.09							
-0.19	-0.11	0.22						
	-0.25	-0.05						
-0.02	0.15	-0.17	0.08	0.24				
-0.15	-0.03	0.23	-0.14	-0.02				
	-0.12	-0.03		0.04	0.09	-0.17		
-0.16	0.06	0.06	-0.09	0.04	-0.04	0.18	0.06	
-0.04	0.06	-0.06	-0.09	0.05	0.06	0.17	0.13	0.03

Max: 0.24 Min: -0.25 RMS: 0.12

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 39: MPACT Problem 2O Power Distribution Comparisons

ENDF/B-VII Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.38	-0.18							
-0.20	-0.02	-0.17						
	-0.40	-0.07						
-0.02	-0.16	0.06	-0.03	-0.17				
-0.21	0.13	0.01	-0.26	0.15				
	-0.11	-0.10		0.21	0.04	-0.13		
-0.11	0.04	0.27	-0.16	0.34	0.04	0.19	0.04	
-0.14	-0.06	-0.16	0.34	0.04	0.13	0.23	0.08	0.15

Max: 0.34 Min: -0.40 RMS: 0.18

MCNP5

-0.49	-0.29							
-0.23	0.00	-0.13						
	-0.44	-0.11						
0.07	-0.09	0.11	0.00	-0.12				
-0.17	0.08	0.03	-0.23	0.15				
	-0.15	-0.13		0.17	0.08	-0.06		
-0.10	0.06	0.25	-0.13	0.30	0.06	0.21	-0.02	
-0.23	-0.02	-0.07	0.29	-0.01	0.07	0.22	0.14	0.13

Max: 0.30 Min: -0.49 RMS: 0.18

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

ENDF/B-VI Normalized Fission Rate Differences (MPACT - Reference) (%)

CE KENO-VI

-0.37	-0.06							
-0.14	0.07	-0.17						
	-0.27	0.04						
0.11	-0.08	0.10	-0.05	-0.20				
-0.23	0.21	0.02	-0.23	0.17				
	-0.11	-0.10		0.21	-0.02	-0.17		
-0.22	0.03	0.29	-0.20	0.38	0.01	0.19	-0.05	
-0.19	-0.09	-0.05	0.33	0.03	0.02	0.06	-0.06	-0.07

Max: 0.38 Min: -0.37 RMS: 0.17

Color Scheme
- Minimum Difference
- Maximum Difference
- Zero Difference

PARAGON 6K

Max: 0.00 Min: 0.00 RMS: 0.00

PARAGON 70g

Max: 0.00 Min: 0.00 RMS: 0.00

Figure 40: MPACT Problem 2P Power Distribution Comparisons

Single Lattice Conclusions

Based on the eigenvalue and pin power comparisons, the following observations can be made.

1. MPACT agrees very well with CE KENO-VI and CE MCNP5 for both eigenvalue and pin power distributions, except for the cases with control rods.
    a. The average ENDF/B-VII eigenvalue difference over all cases is -85 pcm compared to KENO and 42 pcm compared to MCNP.
    b. The average ENDF/B-VI eigenvalue difference over all cases is 1 pcm compared to KENO
    c. The average pin power RMS difference is about 0.15% for both codes and both cross section versions.

2. There appears to be a systematic difference in eigenvalue between MPACT and the CE Monte Carlo codes for rodded cases.
    a. MPACT reactivity prediction of both cross section sets is ~500 pcm higher than the CE Monte Carlo codes.
    b. A systematic difference in the pin power distributions in proximity to the control rodlets is also evident.
    c. These differences are not concerning, because the reactivity and power of rodded core regions is very low. Also, the concept of an infinite array of lattice controlled assemblies is not representative of the actual core configuration, i.e. a finite array of checkerboard controlled assemblies. Rodded multi-assembly cases will be evaluated later in this document.

3. There is a noticeable deterioration of the agreement between MPACT and the CE Monte Carlo for increasing fuel temperature. This trend needs to be further investigated.

4. MPACT v1.0 performs very well based on comparisons to PARAGON results.

5.

MPACT v1.0 ESSM Results

The Embedded Self-Shielding Method (ESSM, Ref. 21) is currently being developed by CASL as a novel approach to performing multi-group cross section processing. The ORNL 60g library created in Reference 9 provided cross sections for use with the ESSM capability in MPACT, which became available for testing with the release of MPACT v1.0 (Ref. 2). For testing purposes and to support future development, each of the Problem 2 lattice case with executed with MPACT using ESSM. The results are provided in Table 8 below. Is it evident from these results that the ESSM methodology in MPACT is premature for application or user testing.

Table 8: MPACT Results Using ESSM Compared to KENO-VI

		Eigenvalues			Pin Powers		
Case	**Description**	**KENO-VI**	**MPACT**	**Diff**	**RMS**	**MAX ABS**	**Runtime (mm:ss)**
2A	565K	1.18251	1.17504	-746	0.09%	0.22%	3:05
2B	600K	1.18403	1.17605	-798	0.08%	0.19%	3:00
2C	900K	1.17443	1.16492	-951	0.08%	0.18%	3:04
2D	1200K	1.16614	1.15588	-1026	0.08%	0.20%	3:04
2E	12 Pyrex	1.07044	1.06378	-666	0.08%	0.17%	3:07
2F	24 Pyrex	0.97690	0.97125	-566	0.13%	0.28%	3:11
2G	24 AIC	0.84924	0.84802	-122	0.18%	0.41%	3:15
2H	24 B4C	0.78975	0.79288	314	0.14%	0.29%	3:11
2I	Instrument Thimble	1.18056	1.17258	-798	0.10%	0.24%	3:08
2J	Instrument + 24 Pyrex	0.97610	0.97050	-560	0.13%	0.29%	3:17
2K	Zoned + 24 Pyrex	1.02100	1.01511	-589	0.11%	0.27%	3:13
2L	80 IFBA	1.01954	1.01255	-699	0.17%	0.38%	22:21
2M	128 IFBA	0.93946	0.93297	-649	0.18%	0.33%	22:33
2N	104 IFBA + 20 WABA	0.87043	0.86510	-533	0.24%	0.43%	23:17
2O	12 Gadolinia	1.04837	1.04167	-670	0.14%	0.36%	3:38
2P	24 Gadolinia	0.92800	0.92315	-485	0.17%	0.39%	3:21

The KENO-VI Uncertainty in eigenvalue is < 3 pcm. The estimated uncertainty in power distribution is < 0.031%
All cases were run with the same quadrature settings as the 60g sub-group results, on the same machines (Fissile Four)

4.2 Multiple 2D Lattices

Multiple 2D assembly configurations are typically simulated to analyze the interaction effects fostered by heterogeneous lattice configurations and characterize the accuracy of the coarse mesh nodal diffusion codes in this scenario. In the CASL reactor physics tools, core analysis will directly be performed using transport-based methodologies. Though approximations may still be made in cross section processing, VERA will essentially perform full core 2D transport for every calculation. Therefore, in VERA we can extend the concept of lattice physics analysis to 2D multi-assembies and 2D cores in order to directly test the capabilities and accuracy of the neutronics tools.

Another advantage of this type of analysis is that configurations more representative of actual core conditions can be studied so that discrepancies that may occur between the codes are quantifiable in the proper context, i.e. closer to, or actual, reactor core configurations.

This progression problem is an escalation from typical lattice physics to larger configurations but is not 3D. It does not directly reside in the ten AMA Core Physics Benchmark Progression Problems. Reference 4 provides the specification of this problem in the section entitled "Miscellaneous Benchmarks" under problem name **4-2D**. This is because it is essentially a 2D slice of Problem 4, as documented in Reference 4.

In particular, problem 4-2D is a 2D slice at the core midplane of the nine assemblies at the center of Watts Bar 1 Cycle 1 startup core. The assemblies are arranged in a checkerboard pattern of five low-enriched (2.11% U-235 w/o) and four middle enriched (2.6% U-235 w/o) assemblies. The middle enriched assemblies feature 20 Pyrex rods. An AIC control rod may be inserted in the centermost assembly (representing the regulating Bank D in Watts Bar 1 core). Because of the symmetry in the 3x3 configuration, this problem may be solved in quadrant or octant symmetry. Figure 41 provides the assembly arrangement and Figure 42 displays the model generated for the KENO-VI reference solution.

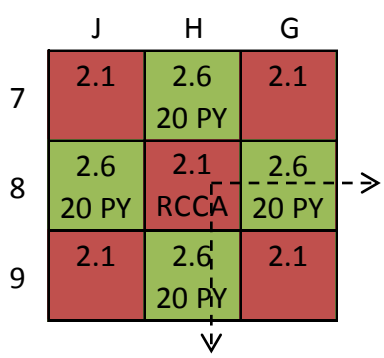


Figure 41: Problem 4-2D Assembly, Pyrex, and Control Rod Arrangement

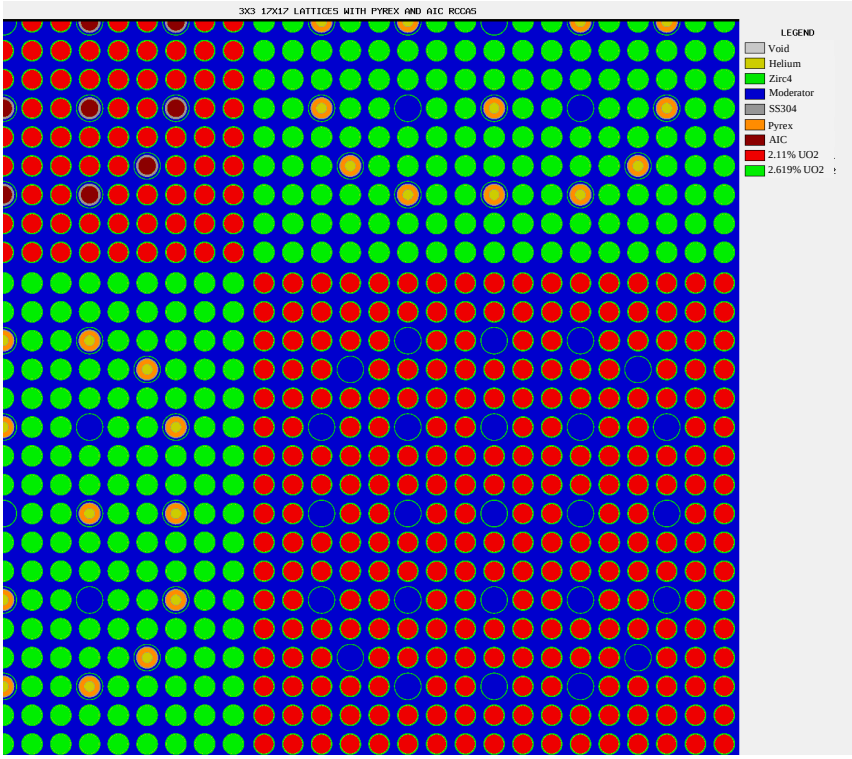


Figure 42: Problem 4-2D Reference Model (with AIC inserted)

A sample MPACT v1.0 input for this problem is provided in Appendix C. Note that, like in the single lattice cases, full symmetry is required due to current limitations in MPACT. Simulations were performed for both uncontrolled and controlled central assembly configurations, with the HELIOS ENDF/B-VI.8 and ORNL ENDF/B-VII.0 cross section libraries. Simulations with PARAGON 70-group ENDF/B-VI.3 and B-VII.0 based libraries. The eigenvalue and pin power results, as well as the calculated rod reactivity worths, are provided in the tables below.

Like the lattice cases, MPACT was executed on one of the Fissile Four machines with the following executable and libraries (a modified version was used to improve the convergence of CMFD for this problem):

Executable / Filename	Date	Checksum
/home/bn7/mpact_bin/bin/MPACT_mod2.exe	12/7/2012 16:51	714502316
/home/bn7/mpact_bin/data/hy047n18g110u.dat	9/18/2012 16:22	2236470032
/home/bn7/mpact_bin/data/declib60g02_e7.fmt	10/12/2012 18:29	863219409

Table 9: MPACT Runtime Performance for Problem 4-2D

	B-VI HELIOS 47g Sub-Group		B-VII ORNL 60g Sub-Group	
Case	**Cores**	**Time (h:mm:ss)**	**Cores**	**Time (h:mm:ss)**
Uncontrolled	8	51:39	16	1:12:05
Controlled	8	54:24	16	1:14:55

Ray parameters used were 0.05/16/2 with C-Y quadrature for all cases

Table 10: MPACT Eigenvalue Comparisons for Problem 4-2D

	Eigenvalues			MPACT Diffs (pcm)	
	KENO-VI CE	PARAGON 70g	MPACT	KENO-VI CE	PARAGON 70g
Uncontrolled B-VI	1.00716		1.00775	59	
Controlled B-VI	0.98036		0.98142	107	
Uncontrolled B-VII	1.01093		1.00992	-101	
Controlled B-VII	0.98416		0.98374	-42	

The KENO-VI uncertainty is less than or equal to 3 pcm.

Table 11: MPACT Rod Worth Comparisons for Problem 4-2D

	Rod Worths (pcm)			MPACT Relative Error	
	KENO-VI CE	PARAGON 70g	MPACT	KENO-VI CE	PARAGON 70g
Rod Worth B-VI	-2715		-2662	-1.9%	
Rod Worth B-VII	-2691		-2635	-2.1%	

Table 12: MPACT Power Distribution Statistics for Problem 4-2D

	MPACT Assy Power RMS Diffs		MPACT Assy Power Max Abs Diffs		MPACT Pin Power RMS Diffs		MPACT Pin Power Max Abs Diffs	
	KENO CE	PAGN 70g	KENO CE	PAGN 70g	KENO CE	PAGN 70g	KENO CE	PAGN 70g
Uncontrolled B-VI	0.10%	--	0.11%	--	0.16%	--	0.48%	--
Controlled B-VI	0.17%	--	0.34%	--	0.21%	--	0.71%	--
Uncontrolled B-VII	0.07%		0.09%		0.16%		0.50%	
Controlled B-VII	0.13%		0.22%		0.21%		0.61%	

PAGN = PARAGON

The KENO-VI estimated uncertainty is less than or equal to 0.13%

1.071	1.050																								
1.070	1.048	1.048																							
	1.066	1.066																							
1.059	1.039	1.040	1.064	1.051																					
1.048	1.027	1.029	1.056	1.058																					
	1.027	1.028		1.033	1.015	0.975																			
0.989	0.972	0.973	0.991	0.972	0.958	0.943	0.930																		
0.920	0.918	0.919	0.922	0.920	0.919	0.917	0.917	0.918																	
1.009	1.012	1.014	1.013	1.022	1.033	1.046	1.062	1.086	0.921																
0.894	0.922	0.924	0.899	0.934	0.962	0.992	1.025	1.066	0.923	0.939															
	0.846	0.849		0.843	0.872	0.936	0.995	1.053	0.926	0.956	0.992														
0.827	0.863	0.874	0.844	0.827		0.874	0.968	1.043	0.931	0.973	1.036														
0.829	0.872	0.911	0.930	0.887	0.829	0.847	0.942	1.034	0.935	0.991	1.057	1.087	1.083												
	0.858	0.942		0.932	0.847		0.909	1.028	0.939	1.013		1.088	1.101												
0.866	0.897	0.925	0.943	0.914	0.878	0.857	0.936	1.031	0.938	0.998	1.058	1.064	1.080	1.111	1.097										
0.951	0.929	0.898	0.860	0.875	0.868	0.855	0.935	1.031	0.939	0.999	1.060	1.065	1.083	1.116	1.103	1.110									
	0.950	0.866		0.832	0.832		0.908	1.029	0.943	1.019		1.090	1.108		1.130	1.137									
0.949	0.926	0.895	0.858	0.874	0.868	0.855	0.937	1.034	0.943	1.004	1.066	1.072	1.091	1.125	1.113	1.120	1.149	1.132							
0.862	0.892	0.921	0.939	0.911	0.877	0.857	0.938	1.036	0.945	1.007	1.070	1.079	1.097	1.130	1.118	1.125	1.154	1.137	1.143						
	0.850	0.934		0.927	0.845		0.913	1.036	0.950	1.028		1.111	1.127		1.144	1.151		1.164	1.171						
0.816	0.858	0.898	0.920	0.879	0.825	0.847	0.946	1.044	0.949	1.011	1.084	1.119	1.120	1.142	1.124	1.130	1.159	1.144	1.151	1.184	1.178				
0.807	0.841	0.853	0.827	0.813		0.870	0.971	1.055	0.949	1.000	1.071		1.137	1.144	1.125	1.130	1.159	1.143	1.152	1.187	1.196				
	0.810	0.814		0.817	0.852	0.924	0.994	1.065	0.949	0.990	1.038	1.094	1.125		1.140	1.148		1.161	1.168		1.183	1.169	1.131		
0.828	0.856	0.860	0.841	0.884	0.922	0.966	1.015	1.076	0.951	0.985	1.018	1.051	1.082	1.117	1.107	1.116	1.143	1.129	1.134	1.158	1.138	1.123	1.109	1.102	
0.890	0.896	0.901	0.906	0.927	0.956	0.991	1.033	1.089	0.959	0.989	1.017	1.043	1.065	1.085	1.093	1.102	1.113	1.115	1.120	1.126	1.120	1.114	1.107	1.104	1.109

Figure 43: Problem 4-2D Uncontrolled MPACT 60g Power Distribution Results

0.547	0.531																								
0.481	0.497	0.487																							
	0.460	0.458																							
0.460	0.486	0.485	0.457	0.472																					
0.471	0.499	0.499	0.466	0.469																					
	0.503	0.505		0.517	0.563	0.638																			
0.552	0.576	0.581	0.568	0.611	0.654	0.700	0.742																		
0.630	0.635	0.641	0.649	0.673	0.704	0.739	0.774	0.807																	
0.776	0.782	0.789	0.798	0.825	0.858	0.898	0.941	0.990	0.863																
0.739	0.766	0.772	0.757	0.802	0.843	0.889	0.941	1.000	0.885	0.917															
	0.744	0.749		0.759	0.794	0.868	0.940	1.012	0.906	0.948	0.998														
0.759	0.792	0.805	0.784	0.772		0.835	0.937	1.023	0.926	0.981	1.056														
0.782	0.824	0.864	0.888	0.852	0.803	0.827	0.930	1.033	0.944	1.011	1.090	1.131	1.138												
	0.831	0.914		0.913	0.836		0.914	1.043	0.962	1.047		1.143	1.166												
0.857	0.887	0.915	0.935	0.911	0.882	0.867	0.954	1.060	0.973	1.042	1.114	1.128	1.153	1.195	1.187										
0.955	0.933	0.902	0.866	0.886	0.884	0.876	0.966	1.073	0.985	1.054	1.126	1.139	1.165	1.208	1.201	1.215									
	0.968	0.883		0.854	0.858		0.949	1.082	0.998	1.085		1.174	1.200		1.238	1.252									
0.977	0.955	0.925	0.889	0.908	0.906	0.897	0.988	1.097	1.006	1.077	1.150	1.162	1.189	1.233	1.225	1.239	1.276	1.263							
0.896	0.929	0.961	0.982	0.956	0.923	0.906	0.998	1.107	1.016	1.088	1.162	1.176	1.202	1.245	1.236	1.249	1.287	1.273	1.284						
	0.893	0.982		0.980	0.896		0.978	1.115	1.027	1.116		1.218	1.241		1.270	1.283		1.307	1.318						
0.864	0.909	0.952	0.976	0.935	0.880	0.909	1.019	1.129	1.031	1.103	1.187	1.231	1.238	1.267	1.252	1.264	1.301	1.287	1.299	1.340	1.336				
0.858	0.896	0.909	0.883	0.870		0.939	1.051	1.145	1.035	1.095	1.178		1.260	1.273	1.256	1.266	1.303	1.289	1.302	1.346	1.358				
	0.866	0.872		0.879	0.918	1.000	1.079	1.160	1.038	1.087	1.144	1.210	1.250		1.276	1.288		1.312	1.323		1.346	1.331	1.290		
0.888	0.918	0.924	0.905	0.953	0.996	1.047	1.105	1.174	1.042	1.084	1.124	1.165	1.203	1.247	1.240	1.254	1.288	1.276	1.286	1.316	1.295	1.280	1.266	1.258	
0.956	0.962	0.968	0.975	1.001	1.034	1.076	1.125	1.190	1.052	1.089	1.123	1.157	1.186	1.212	1.225	1.239	1.255	1.261	1.270	1.280	1.276	1.271	1.264	1.261	1.268

Figure 44: Problem 4-2D Controlled MPACT 60g Power Distribution Results

Differences from
CE KENO-VI

-0.2%	-0.2%																								
-0.1%	0.0%	-0.1%																							
	-0.2%	-0.2%																							
-0.3%	-0.1%	0.0%	-0.2%	0.0%																					
-0.2%	-0.3%	-0.1%	-0.2%	-0.1%																					
	-0.3%	-0.2%		-0.2%	-0.1%	0.1%																			
-0.1%	-0.1%	-0.1%	-0.1%	0.0%	-0.1%	0.1%	0.0%																		
-0.1%	0.0%	0.0%	-0.2%	0.0%	0.0%	0.0%	0.1%	0.1%																	
-0.1%	-0.1%	0.0%	-0.1%	-0.1%	0.1%	0.1%	0.1%	0.1%	0.2%																
0.0%	0.0%	-0.2%	0.0%	0.0%	0.1%	0.0%	0.2%	0.1%	0.1%	0.0%															
	0.1%	0.0%		0.0%	0.2%	0.0%	0.1%	0.1%	0.1%	0.0%	-0.1%														
0.1%	-0.2%	0.0%	0.0%	0.1%		0.2%	0.1%	0.0%	0.0%	0.0%	-0.1%														
-0.1%	-0.2%	-0.2%	-0.1%	-0.1%	0.1%	-0.1%	0.0%	-0.2%	-0.1%	0.0%	-0.1%	-0.2%	-0.1%												
	-0.1%	-0.2%		-0.1%	0.0%		0.0%	0.0%	0.0%	-0.1%		-0.3%	-0.3%												
-0.2%	-0.3%	-0.2%	-0.2%	-0.1%	-0.1%	0.0%	-0.2%	-0.1%	0.0%	0.0%	-0.1%	-0.1%	0.1%	-0.2%	0.0%										
-0.2%	-0.1%	-0.3%	-0.2%	-0.2%	-0.2%	0.1%	-0.2%	-0.1%	0.0%	-0.1%	-0.1%	-0.1%	0.0%	-0.1%	0.0%	0.0%									
	-0.2%	-0.2%		-0.1%	0.0%		0.0%	0.0%	0.0%	-0.1%		-0.1%	-0.1%		0.0%	0.0%									
-0.3%	-0.2%	-0.3%	-0.1%	-0.1%	-0.1%	0.1%	-0.1%	0.0%	-0.2%	-0.1%	-0.2%	0.1%	0.0%	-0.1%	0.0%	0.1%	0.1%	0.2%							
-0.2%	-0.3%	-0.3%	-0.3%	-0.2%	-0.1%	0.1%	-0.1%	-0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	-0.1%	0.1%	0.1%	0.0%	0.1%	0.1%						
	-0.2%	-0.2%		-0.1%	-0.1%		0.1%	0.1%	0.0%	0.0%		-0.2%	-0.1%		0.0%	0.0%		0.0%	0.1%						
-0.1%	-0.2%	-0.2%	-0.2%	-0.1%	-0.1%	0.0%	0.0%	0.1%	-0.1%	0.1%	-0.1%	0.1%	0.0%	-0.1%	0.0%	0.1%	0.2%	0.2%	0.2%	0.1%	0.2%				
-0.1%	-0.3%	-0.2%	0.0%	-0.1%		0.1%	0.1%	0.1%	0.2%	0.1%	0.0%		0.0%	0.0%	0.2%	0.1%	-0.1%	0.2%	0.2%	0.1%	0.4%				
	0.0%	0.0%		-0.1%	0.2%	0.1%	0.0%	0.1%	0.2%	0.2%	0.2%	0.1%	0.0%		0.1%	0.1%		0.3%	0.2%		0.3%	0.2%	0.4%		
-0.2%	-0.2%	-0.2%	-0.1%	-0.1%	0.1%	0.1%	0.2%	0.2%	0.1%	0.2%	0.2%	0.1%	0.3%	0.2%	0.2%	0.3%	0.3%	0.2%	0.2%	0.3%	0.3%	0.3%	0.4%	0.4%	
-0.1%	-0.1%	-0.2%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.1%	0.2%	0.2%	0.2%	0.3%	0.1%	0.2%	0.2%	0.1%	0.3%	0.2%	0.3%	0.3%	0.4%	0.4%	0.4%	0.5%

Figure 45: Problem 4-2D ENDF/B-VII Uncontrolled MPACT Pin Power Differences

Differences from
CE KENO-VI

-0.5%	-0.5%																							
-0.5%	-0.6%	-0.4%																						
	-0.3%	-0.2%																						
-0.3%	-0.4%	-0.3%	0.0%	-0.2%																				
0.0%	-0.1%	-0.3%	0.0%	-0.1%																				
	-0.1%	-0.1%		-0.1%	-0.1%	0.0%																		
-0.3%	-0.3%	-0.4%	-0.2%	-0.2%	-0.1%	-0.2%	-0.2%																	
-0.3%	-0.4%	-0.3%	-0.2%	-0.2%	-0.1%	-0.2%	-0.1%	-0.1%																
-0.3%	-0.4%	-0.3%	-0.3%	-0.2%	-0.1%	-0.1%	-0.1%	-0.1%	0.0%															
-0.3%	-0.3%	-0.3%	-0.2%	-0.2%	-0.1%	-0.1%	0.0%	0.0%	0.0%	0.1%														
	-0.1%	-0.2%		-0.1%	0.0%	0.0%	0.0%	-0.1%	0.0%	0.0%	0.1%													
-0.1%	-0.4%	-0.3%	-0.2%	-0.1%		0.1%	-0.1%	0.0%	0.1%	-0.1%	0.0%													
-0.3%	-0.3%	-0.2%	-0.3%	-0.2%	-0.1%	0.1%	0.0%	0.1%	0.0%	0.1%	-0.1%	0.0%	0.0%											
	-0.2%	-0.2%		-0.2%	0.0%		0.1%	0.0%	0.0%	0.1%		-0.2%	-0.1%											
-0.3%	-0.4%	-0.3%	-0.3%	-0.1%	0.0%	0.1%	0.0%	0.1%	0.2%	0.0%	-0.2%	0.0%	0.0%	-0.2%	-0.1%									
-0.3%	-0.3%	-0.4%	-0.2%	-0.2%	-0.2%	0.2%	0.0%	0.1%	0.1%	0.0%	0.0%	0.1%	0.0%	0.0%	0.2%	0.2%								
	-0.1%	-0.2%		-0.1%	0.0%		0.1%	0.1%	0.0%	0.1%		0.0%	-0.2%		0.0%	0.1%								
-0.4%	-0.2%	-0.4%	-0.2%	-0.2%	-0.3%	0.2%	-0.1%	0.0%	0.0%	-0.1%	-0.1%	-0.1%	0.1%	0.1%	0.3%	0.1%	0.1%	0.2%						
-0.3%	-0.4%	-0.2%	-0.2%	-0.2%	-0.1%	0.1%	-0.1%	0.0%	0.2%	0.1%	-0.1%	0.1%	0.0%	-0.1%	0.2%	0.2%	0.0%	0.2%	0.4%					
	-0.3%	-0.3%		0.1%	0.0%		0.1%	0.1%	0.0%	0.0%		0.0%	-0.1%		0.0%	0.1%		0.1%	0.1%					
-0.2%	-0.2%	-0.2%	-0.1%	0.0%	-0.1%	0.1%	-0.1%	0.0%	0.2%	0.2%	0.1%	0.1%	0.3%	0.0%	0.2%	0.1%	0.1%	0.4%	0.3%	0.1%	0.3%			
0.1%	-0.3%	-0.2%	0.0%	0.0%		0.2%	0.1%	0.3%	0.2%	0.2%	0.1%		0.1%	0.2%	0.2%	0.1%	0.0%	0.3%	0.2%	0.2%	0.2%			
	-0.1%	-0.1%		-0.1%	0.1%	0.1%	0.2%	0.2%	0.2%	0.1%	0.3%	0.2%	0.2%		0.1%	0.2%		0.0%	0.3%		0.3%	0.4%	0.4%	
-0.1%	-0.2%	-0.2%	-0.1%	-0.1%	0.1%	0.0%	0.3%	0.2%	0.3%	0.4%	0.2%	0.1%	0.3%	0.3%	0.3%	0.3%	0.2%	0.3%	0.3%	0.3%	0.5%	0.3%	0.6%	0.6%
-0.1%	-0.2%	-0.2%	-0.1%	0.0%	0.1%	0.1%	0.2%	0.2%	0.3%	0.2%	0.3%	0.2%	0.2%	0.3%	0.2%	0.2%	0.3%	0.4%	0.2%	0.3%	0.4%	0.4%	0.5%	0.6%	0.5%

Figure 46: Problem 4-2D ENDF/B-VII Controlled MPACT Pin Power Differences

Uncontrolled

0.0%	0.0%																								
-0.2%	0.1%	0.0%																							
	0.0%	-0.3%																							
-0.2%	-0.1%	-0.1%	-0.2%	0.0%																					
-0.2%	-0.1%	0.0%	-0.3%	-0.2%																					
	-0.2%	-0.2%		-0.1%	-0.2%	0.1%																			
-0.1%	0.0%	0.0%	-0.1%	0.1%	-0.1%	0.0%	0.1%																		
0.1%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%																	
0.2%	0.0%	0.1%	0.1%	0.1%	0.0%	-0.1%	0.0%	0.0%	0.1%																
0.2%	0.0%	-0.1%	0.2%	0.1%	0.1%	0.0%	0.2%	0.0%	0.0%	0.0%															
	0.4%	0.3%		0.3%	0.2%	0.1%	0.1%	-0.1%	0.0%	-0.1%	-0.2%														
0.4%	0.0%	0.1%	0.3%	0.3%		0.3%	0.1%	0.0%	0.0%	0.0%	-0.2%														
0.1%	0.0%	0.2%	0.0%	0.1%	0.2%	0.4%	0.1%	0.0%	0.0%	-0.1%	-0.2%	-0.1%	0.0%												
	0.2%	0.0%		0.1%	0.3%		0.3%	0.1%	0.0%	-0.2%		-0.2%	-0.3%												
0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.3%	0.1%	0.0%	-0.1%	0.0%	-0.3%	-0.2%	-0.1%	-0.3%	-0.1%										
0.0%	0.1%	0.0%	0.1%	-0.1%	0.1%	0.3%	-0.1%	0.1%	0.0%	-0.1%	-0.1%	0.0%	-0.2%	-0.2%	-0.1%	-0.2%									
	0.0%	0.1%		0.2%	0.3%		0.2%	0.2%	-0.1%	-0.2%		-0.3%	-0.3%		-0.1%	-0.1%									
0.1%	0.1%	0.0%	0.1%	0.0%	0.1%	0.5%	0.0%	0.1%	0.0%	0.0%	-0.2%	-0.2%	0.0%	-0.2%	-0.2%	-0.1%	-0.1%	-0.1%							
0.0%	-0.1%	0.0%	0.1%	0.1%	0.0%	0.2%	0.1%	-0.1%	0.0%	0.0%	-0.2%	0.0%	-0.1%	-0.2%	-0.2%	-0.1%	-0.1%	-0.2%	0.0%						
	0.1%	0.0%		0.2%	0.4%		0.2%	0.0%	0.0%	-0.1%		-0.4%	-0.3%		-0.3%	-0.2%		-0.2%	-0.1%						
0.2%	0.0%	0.0%	0.1%	0.1%	0.3%	0.4%	0.1%	0.0%	-0.1%	-0.1%	-0.2%	0.0%	-0.1%	-0.3%	-0.1%	-0.2%	-0.3%	-0.1%	0.0%	-0.2%	0.0%				
0.2%	0.0%	0.1%	0.2%	0.3%		0.4%	0.2%	0.1%	0.0%	0.0%	-0.1%		-0.2%	-0.2%	0.0%	0.1%	-0.3%	-0.1%	0.1%	-0.3%	-0.1%				
	0.3%	0.3%		0.3%	0.3%	0.1%	0.0%	0.1%	0.0%	0.0%	0.0%	-0.3%	-0.2%		-0.2%	-0.1%		-0.1%	-0.1%		0.0%	0.0%	0.2%		
0.2%	0.0%	0.1%	0.3%	0.1%	0.0%	0.1%	0.1%	0.0%	0.0%	0.0%	-0.1%	-0.1%	0.0%	-0.2%	-0.1%	0.0%	-0.2%	0.0%	0.0%	-0.1%	0.0%	-0.1%	0.0%	0.2%	
0.3%	0.0%	0.0%	0.2%	0.1%	0.1%	0.2%	0.0%	-0.2%	0.0%	0.0%	0.0%	-0.1%	-0.1%	-0.3%	0.0%	-0.1%	0.0%	-0.1%	-0.1%	-0.1%	-0.2%	0.2%	0.1%	0.0%	0.3%

Controlled

0.3%	0.3%																								
0.4%	0.2%	0.2%																							
	0.4%	0.6%																							
0.6%	0.3%	0.3%	0.6%	0.3%																					
0.4%	0.3%	0.4%	0.7%	0.6%																					
	0.6%	0.5%		0.4%	0.5%	0.2%																			
0.3%	0.2%	0.2%	0.4%	0.2%	0.3%	0.2%	0.2%																		
0.2%	0.2%	0.1%	0.2%	0.2%	0.3%	0.1%	0.1%	0.3%																	
0.1%	0.1%	0.1%	0.3%	0.1%	0.0%	0.0%	0.0%	-0.1%	0.1%																
0.2%	0.0%	0.0%	0.2%	0.1%	0.1%	0.1%	0.1%	-0.1%	0.1%	0.2%															
	0.3%	0.3%		0.1%	0.2%	0.0%	0.0%	-0.1%	-0.1%	0.0%	-0.1%														
0.2%	0.1%	0.0%	0.3%	0.2%		0.3%	0.1%	0.0%	0.1%	0.0%	-0.2%														
0.3%	0.0%	0.1%	0.1%	0.2%	0.3%	0.4%	0.1%	0.0%	-0.1%	0.0%	-0.1%	-0.2%	-0.1%												
	0.1%	0.1%		0.2%	0.3%		0.1%	0.1%	-0.1%	-0.1%		-0.2%	-0.3%												
0.1%	-0.1%	0.2%	0.0%	0.0%	0.1%	0.2%	0.0%	0.0%	0.0%	-0.1%	-0.3%	-0.3%	-0.1%	-0.4%	-0.2%										
0.1%	-0.1%	-0.1%	0.1%	0.0%	0.1%	0.2%	0.1%	0.0%	0.0%	-0.1%	-0.2%	-0.1%	-0.1%	-0.2%	-0.2%	-0.2%									
	0.0%	0.1%		0.2%	0.3%		0.2%	0.1%	0.1%	-0.3%		-0.4%	-0.4%		-0.2%	-0.3%									
-0.1%	-0.1%	0.0%	0.1%	0.1%	0.0%	0.5%	-0.1%	0.0%	0.0%	-0.2%	-0.2%	-0.2%	-0.2%	-0.3%	-0.2%	0.0%	-0.3%	-0.1%							
0.0%	-0.1%	0.0%	-0.1%	0.0%	0.1%	0.3%	-0.1%	0.0%	-0.2%	-0.1%	-0.3%	-0.1%	-0.2%	-0.5%	-0.1%	0.0%	-0.3%	-0.1%	-0.3%						
	0.0%	-0.1%		0.1%	0.3%		0.1%	0.0%	-0.1%	-0.2%		-0.4%	-0.3%		-0.3%	-0.3%		-0.4%	-0.3%						
0.1%	-0.1%	0.0%	-0.1%	0.1%	0.2%	0.3%	0.0%	0.1%	-0.1%	-0.2%	-0.2%	-0.3%	-0.1%	-0.3%	-0.1%	-0.1%	-0.3%	-0.1%	-0.2%	-0.4%	-0.3%				
0.2%	0.0%	0.0%	0.2%	0.2%		0.3%	0.1%	0.0%	-0.1%	-0.1%	-0.2%		-0.2%	-0.4%	-0.2%	-0.1%	-0.3%	-0.2%	-0.1%	-0.4%	-0.2%				
	0.2%	0.1%		0.2%	0.3%	0.0%	0.0%	0.0%	-0.1%	-0.2%	-0.1%	-0.3%	-0.2%		-0.3%	-0.2%		-0.3%	-0.4%		-0.2%	-0.2%	-0.1%		
0.2%	-0.1%	0.0%	0.1%	-0.1%	0.0%	-0.1%	0.0%	-0.1%	0.0%	0.0%	-0.2%	-0.1%	-0.1%	-0.2%	-0.1%	0.0%	-0.1%	-0.3%	-0.1%	-0.2%	0.0%	0.0%	-0.2%	-0.2%	
0.1%	0.0%	0.0%	0.1%	0.1%	0.0%	-0.1%	0.0%	-0.2%	-0.1%	0.0%	-0.2%	-0.1%	-0.1%	-0.2%	-0.1%	-0.2%	-0.1%	0.0%	-0.2%	-0.2%	-0.2%	-0.2%	-0.2%	0.0%	0.0%

Figure 47: Problem 4-2D ENDF/B-VI MPACT Pin Power Differences

2D 3x3 Conclusions

The reactivity comparisons of MPACT v1.0 to KENO-VI and PARAGON are generally very good for the 3x3 assembly case. The difference with KENO is less than 107 pcm for all cases, including both rodded and unrodded configurations with either cross section libraries. Also, the control rod worth agrees to within 2.1%. Finally, the pin power distribution agreement between MPACT and KENO is also very good with RMS difference of around 0.2% and peak pin difference of about 0.7%.

Finally, observing the distribution of differences in Figures 44-46, it is clear that the ENDF/B-VI cross sections result in a bias for fuel rods next to guide tubes. For the controlled case, the pins next to empty guide tubes are underpredicted, while the fission rate is overpredicted in pins next to Pyrex or AIC absorbers. This trend is not seen in the ENDF/B-VII results, which may indicate that the ORNL 60g sub-group library is performing slightly better than the HELIOS 47g sub-group library, or it could result from comparing a consistent set of base cross sections from SCALE.

The MPACT runtime performance for the 2D 3x3 is much longer than what expected by scaling the single lattice runtime . This aspect deserves further investigation. The runtime performance of the multi-assembly MPACT cases would also greatly benefit from the capability of running quadrant or even octant symmetry.

As previously discussed, the accuracy of MPACT in the rodded 3x3 configurations greatly exceeds that of the single rodded lattice. This indicates that the discrepancies observed for the results of Problems 2G and 2H are unimportant when considering realistic configurations, representative of actual reactor cores.

CONCLUSIONS AND FEEDBACK

1. MPACT v1.0 agrees very well with CE KENO-VI and CE MCNP5 for both ENDF/B-VI and ENDF/B-VII cross section libraries. The two controlled single-assembly calculations exhibit a larger bias, ~500 pcm, , but the excellent agreement of the rodded 3x3 assembly analysis seems to indicate that this could not be a significant problem in realistic core configurations.

2. There is a small but evident deterioration in the agreement between MPACT and the CE Monte Carlo codes with increasing fuel temperature. This trend needs to be further investigated.

3. MPACT v1.0 performs very well based on comparisons to PARAGON results. [

   ]

4. The MPACT runtimes still need some investigation. The lattice calculations are significantly slower than PARAGON with the 70 group library, and the 2D multi-assembly problems were disproportionately slow compared to the single lattice calculations. Simulation of 2D quarter core problems could provide an important feedback in the interim time towards simulating 3D problems.

5. The ORNL 60g sub-group library shows very good performance for the simulations and configurations performed, though the runtime performance may not be optimal.

6. The ESSM methodology is currently performing poorly in MPACT and needs more development and testing time before AMA can properly evaluate it.

7. The IFBA cases can be accurately predicted in MPACT at the computational cost of significantly decreasing the MOC ray spacing, resulting in extremely long run times. This does not appear to be practical for larger or full core problems containing IFBA. Therefore a more efficient methodology for treating IFBA appears to be required.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Ben Collins of University of Michigan for providing excellent support to the users of MPACT.

REFERENCES

1. B. Collins, et al, "MPACT 0.2.2", Revision 0, CASL-U-2012-XXXX-000, CASL, June 30, 2012.
2. B. Collins, email with subject "MPACT Release v1.0.0", 11/21/2012. (Appendix A)
3. MPACT User Manual, v1.0.0, University of Michigan, 11/28/2012.
4. A.T. Godfrey, "VERA Core Physics Benchmark Progression Problem Specifications", CASL-U-2012-0131-001, CASL, 12/21/2012.
5. D. F. Hollenbach, L. M. Petrie, and N. F. Landers, "KENO-VI: A General Quadratic Version of the KENO Program," Vol. II, Sect. F17 of SCALE: A Modular Code System for Performing Standardized Computer Analysis for Licensing Evaluation, NUREG/CR-0200, Rev. 7 (ORNL/NUREG/CR/CSD-2R7), 3 vols., April 2004. Available from the Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-545.
6. X-5 Monte Carlo Team, MCNP—A general Monte Carlo N-Particle Transport Code, Version 5, vol. 1, LA-UR-03-1987, 2003. http://mcnp.lanl.gov/ http://rsicc.ornl.gov
7. M. Ouisloumen, et al., "The New Westinghouse Assembly Lattice Code, ANS International Meeting on Mathematical Methods for Nuclear Applications, Salt Lake City, Utah, USA (2001)
8. "Qualification of Nuclear Design Methodology using PARAGON/ANC", Non-Proprietary Version, MUAP-07019-NP (R0), Mitsubishi Heavy Industries, Ltd., December 2007. http://pbadupws.nrc.gov/docs/ML0802/ML080250228.pdf
9. Generation of Multigroup Nuclear Data Libraries for CASL, ORNL, Completion report for CASL milestone L3:RTM.SUP.P5.02, 9/28/2012.
10. DeCART v2.05 User's Manual, University of Michigan, 2009.
11. SCALE: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design, ORNL/TM-2005/39, Version 6.1, June 2011. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-785.
12. U. Decher, et al., "ENDF/B-VI Performance in PWR Applications", Trans. Am. Nucl. Soc.,73,417, 1995.
13. H. C. Huria and M. Ouisloumen, "Integral Data Testing for Thermal Spectrum Critical Experiments using ENDF/B-VII.0", Advances in Nuclear Fuel Management IV, Hilton Head Island, South Carolina, USA, April,2009.
14. H.C. Huria, V. N. Kucukboyaci, and M. Ouisloumen, "ENDF/B-VII.0 Based Library for PARAGON" PHYSOR 2010 – Advances in Reactor Physics to Power the Nuclear Renaissance, Pittsburgh, Pennsylvania, USA, May 9-14, 2010.
15. V. N. Kucukboyaci, H. C. Huria, and M. Ouisloumen, "PARAGON Library with 4.0eV Upscattering Cut-Off", PHYSOR 2010 – Advances in Reactor Physics to Power the Nuclear Renaissance, Pittsburgh, Pennsylvania, USA, May 9-14, 2010.
16. H.C. Huria and M. Ouisloumen, "An optimized ultra-fine energy group structure for neutron transport calculations", International Conference on the Physics of Reactors (PHYSOR 2008), Interlaken, Switzerland, 2008.
17. M. Ouisloumen et al.,"Qualification of the Two-Dimensional Transport Code PARAGON', WCAP-16045-NP-A, August, 2004.
18. B. Zhang, et. Al., "Qualification of the NEXUS Nuclear Data Methodology", WCAP-16045-NP-A, Addendum 1, November, 2005.
19. V.N. Kucukboyaci, F. Franceschini and M. Ouisloumen, "Two-Dimensional Whole Core Transport Calculations Using PARAGON", International Conference on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, May 3-7, 2009.

20. L. Mayhue, et.al., “Qualification of NEXUS ANC Nuclear Design System for PWR Analyses”, International Conference on the Physics of Reactors (PHYSOR 2008), Interlaken, Switzerland, 2008
21. M. L. Williams and K. S. Kim, "The Embedded Self-Shielding Method," PHYSOR 2012 Advances in Reactor Physics Linking Research, Industry, and Education, Knoxville, Tenn., April 15-20, 2012, on CD-ROM, American Nuclear Society, LaGrange Park, Ill. (2012)
22. S. Hess, “VERA Requirements Document (VRD) – Revision 1”, CASL-I-2011-0074-002, CASL, March, 2012.
23. *Ganglia:: Fissile Systems Cluster* Report (2012). Retrieved December 17, 2012, from http://casl-dev.ornl.gov/ganglia/

APPENDIX A – EMAIL REGARDING MPACT V1.0 RELEASE

Email from Benjamin Collins, Dated 11/21/2012, regarding the delivery of MPACT v1.0:

From: Ben Collins [mailto:bscollin@umich.edu]
Sent: Wednesday, November 21, 2012 5:31 PM
To: Palmtag, Scott; Godfrey, Andrew T.; Gehin, Jess C.; William Martin; Edward Larsen; John Lee; Thomas Downar; Evans, Thomas M.; decart-dev@umich.edu; tjd-countm@umich.edu; Turner, John A.; Scott Palmtag
Subject: MPACT Release v1.0.0

On behalf of the MPACT development team I would like to announce the the official release of MPACT v1.0.0. This release has some new key features which greatly improve the run time over previous versions. Most significantly, CMFD has been added for 2D problems. There are several other features listed below:

- 2D and 3D MOC and CDP transport kernels
- CMFD acceleration for 2D problems
- Cross-section shielding with Subgroup and ESSM
- Support for the HELIOS and ORNL subgroup libraries
- Visualization via VisIt
- much much more.

I'd like to thank the entire MPACT development team for all their hard work to make this happen.

--
Ben Collins
Assistant Research Scientist
University of Michigan
Department of Nuclear Engineering and Radiological Sciences
Ann Arbor, MI 48105
(734) 647-3185

APPENDIX B –MPACT INPUT FOR 2D LATTICE

MPACT input for Problem 2A.

```
CASEID mpact_2a

!  Material 1:  Fuel
!  Material 2:  Gap
!  Material 3:  Clad
!  Material 4:  Water
MATERIAL
  mat  1 2 10.257   g/cc  565 K \ 92235  7.18132E-04
                                  92236  3.29861E-06
                                  92234  6.11864E-06
                                  92238  2.21546E-02
                                   8001  4.57642E-02
  mat  2 0 1.786e-4 g/cc  565 K \  8016  2.68714E-05
  mat  3 4 6.56     g/cc  565 K \ 50124  2.79392E-05
                                  50122  2.23417E-05
                                  26056  1.36306E-04
                                  26054  8.68307E-06
                                  50118  1.16872E-04
                                  50117  3.70592E-05
                                  50120  1.57212E-04
                                  50119  4.14504E-05
                                  24053  7.21860E-06
                                  24052  6.36606E-05
                                  72174  3.54138E-09
                                  24054  1.79686E-06
                                  26058  4.18926E-07
                                  26057  3.14789E-06
                                  24050  3.30121E-06
                                  72180  7.76449E-07
                                  72176  1.16423E-07
                                  40091  4.77292E-03
                                  40090  2.18865E-02
                                  72178  6.03806E-07
                                  72179  3.01460E-07
                                  72177  4.11686E-07
                                  50114  3.18478E-06
                                  50112  4.68066E-06
                                  50116  7.01616E-05
                                  50115  1.64064E-06
                                  40094  7.39335E-03
                                  40092  7.29551E-03
                                  40096  1.19110E-03
  mat  4 0 0.743    g/cc  565 K \  5010  1.07070E-05
                                   5011  4.30971E-05
                                   1001  4.96224E-02
                                   8016  2.48112E-02
GEOM
!Ray tracing module dimensions
  mod_dim 21.50 21.50 1.0

  pinmesh 1 cyl 0.4096 0.418 0.475 0.575 / 1.26 / 1 / 3 1 1 1 / 7*8 / 1 ! Fuel
  pinmesh 2 cyl              0.561 0.602 / 1.26 / 1 /     2 1 / 4*8 / 1 ! Guide tube

  pinMesh 3 rec 0.04 / 0.04 / 1 / 1 / 1 / 1   ! Water gap
  pinMesh 4 rec 1.26 / 0.04 / 1 / 4 / 1 / 1   ! Water gap
  pinMesh 5 rec 0.04 / 1.26 / 1 / 1 / 4 / 1   ! Water gap

  pin  1 1 / 3*1 2 3 4 4   ! pin cell
  pin  2 2 / 2*4 3 4       ! guide tube
  pin  3 3 / 4             ! Corner Assembly gap
  pin  4 4 / 4             ! N & S Assembly gap
  pin  5 5 / 4             ! W & E Assembly gap
```

```
!Pin modular ray tracing
  module 1 2*19 1
   3  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  3
   5  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  5
   5  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  5
   5  1  1  1  1  1  2  1  1  2  1  1  2  1  1  1  1  1  5
   5  1  1  1  2  1  1  1  1  1  1  1  1  1  2  1  1  1  5
   5  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  5
   5  1  1  2  1  1  2  1  1  2  1  1  2  1  1  2  1  1  5
   5  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  5
   5  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  5
   5  1  1  2  1  1  2  1  1  2  1  1  2  1  1  2  1  1  5
   5  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  5
   5  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  5
   5  1  1  2  1  1  2  1  1  2  1  1  2  1  1  2  1  1  5
   5  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  5
   5  1  1  1  2  1  1  1  1  1  1  1  1  1  2  1  1  1  5
   5  1  1  1  1  1  2  1  1  2  1  1  2  1  1  1  1  1  5
   5  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  5
   5  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  5
   3  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  4  3

  lattice 1 2*1
   1

  assembly 1
   1
  core 360
   1

XSEC
  addpath ../
  xslib ORNL declib60g02_e7.fmt

OPTION
  bound_cond 1 1 1 1 1 1
  solver 1 2
  ray 0.05 CHEBYSHEV-YAMAMOTO 16 2
  parallel 1 1 1 8
  conv_crit 2*1.e-5
  iter_lim 2000 2 3
  vis_edits T
  validation T C
.
```

APPENDIX C –MPACT INPUT FOR 2D 3X3

MPACT input for Problem 4-2D.

```
CASEID mpact_4_2d_con

!  Material 1:  Fuel 2.1%
!  Material 2:  Fuel 2.6%
!  Material 3:  Gap
!  Material 4:  Clad
!  Material 5:  Water
!  Material 6:  Pyrex
!  Material 7:  SS304
!  Material 8:  AIC
MATERIAL
  mat  1 2 10.257   g/cc  600 K \  8001  4.57591E-02
                                 92234  4.04814E-06
                                 92235  4.88801E-04
                                 92236  2.23756E-06
                                 92238  2.23844E-02
  mat  2 2 10.257   g/cc  600 K \  8001  4.57617E-02
                                 92234  5.09503E-06
                                 92235  6.06709E-04
                                 92236  2.76809E-06
                                 92238  2.22663E-02
  mat  3 0 1.786e-4 g/cc  600 K \  8016  2.68714E-05
  mat  4 4 6.56     g/cc  600 K \ 26057  3.14789E-06
                                 26056  1.36306E-04
                                 24050  3.30121E-06
                                 26058  4.18926E-07
                                 50120  1.57212E-04
                                 50122  2.23417E-05
                                 50119  4.14504E-05
                                 26054  8.68307E-06
                                 50124  2.79392E-05
                                 72177  4.11686E-07
                                 72176  1.16423E-07
                                 72179  3.01460E-07
                                 72178  6.03806E-07
                                 24053  7.21860E-06
                                 24052  6.36606E-05
                                 72174  3.54138E-09
                                 24054  1.79686E-06
                                 40094  7.39335E-03
                                 40092  7.29551E-03
                                 40096  1.19110E-03
                                 40090  2.18865E-02
                                 72180  7.76449E-07
                                 40091  4.77292E-03
                                 50117  3.70592E-05
                                 50116  7.01616E-05
                                 50118  1.16872E-04
                                 50114  3.18478E-06
                                 50112  4.68066E-06
                                 50115  1.64064E-06
  mat  5 0 0.743    g/cc  600 K \  1001  4.96224E-02
                                  5010  1.07070E-05
                                  5011  4.30971E-05
                                  8016  2.48112E-02
  mat  6 0 2.25     g/cc  600 K \  5010  9.63266E-04
                                  5011  3.90172E-03
                                  8016  4.67761E-02
                                 14000  1.97326E-02
  mat  7 0 8.00     g/cc  600 K \  6000  3.20895E-04
                                 14000  1.71537E-03
                                 15031  6.99938E-05
```

```
                                  24050  7.64915E-04
                                  24052  1.47506E-02
                                  24053  1.67260E-03
                                  24054  4.16346E-04
                                  25055  1.75387E-03
                                  26054  3.44776E-03
                                  26056  5.41225E-02
                                  26057  1.24992E-03
                                  26058  1.66342E-04
                                  28058  5.30854E-03
                                  28060  2.04484E-03
                                  28061  8.88879E-05
                                  28062  2.83413E-04
                                  28064  7.21770E-05
  mat  8 4 10.2     g/cc  600 K \ 47107  2.36159E-02
                                  47109  2.19403E-02
                                  48000  2.73220E-03
                                  49113  3.44262E-04
                                  49115  7.68050E-03
GEOM
!Ray tracing module dimensions
  mod_dim 21.50 21.50 1.0

  pinmesh 1 cyl 0.4096 0.418 0.475 0.575 / 1.26 / 1 / 3 1 1 1 / 7*8 / 1  ! fuel rod
  pinmesh 2 cyl              0.561 0.602 / 1.26 / 1 /     2 1 / 4*8 / 1  ! guide tube
  pinmesh 3 cyl 0.214 0.231 0.241 0.427 0.437 0.484 0.561 0.602/1.26/1/8*1/9*8 /1 ! pyrex
  pinmesh 4 cyl  0.382 0.386 0.484 0.561 0.602 / 1.26 / 1 / 3 1 1 1 1 / 8*8 / 1 ! RCCA

  pinMesh 5 rec 1.26 / 0.04 / 1 / 4 / 1 / 1  ! Water gap
  pinMesh 6 rec 0.04 / 1.26 / 1 / 1 / 4 / 1  ! Water gap
  pinMesh 7 rec 0.04 / 0.04 / 1 / 1 / 1 / 1  ! Water gap

  pin  1 1 / 3*1 3 4 5 5          ! 2.1% pin cell
  pin  2 1 / 3*2 3 4 5 5          ! 2.6% pin cell
  pin  3 2 / 2*5 4 5              ! guide tube
  pin  4 3 / 3 7 3 6 3 7 5 4 5    ! pyrex in guide tube
  pin  5 4 / 3*8 3 7 5 4 5        ! AIC in guide tube

  pin  6 5 / 5                    ! N & S Assembly gap
  pin  7 6 / 5                    ! W & E Assembly gap
  pin  8 7 / 5                    ! Corner Assembly gap

!Assembly modular ray tracing

!2.1% assembly with empty guide tubes
 module 1 2*19 1
    8  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  8
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  1  1  3  1  1  3  1  1  3  1  1  1  1  1  7
    7  1  1  1  3  1  1  1  1  1  1  1  1  1  3  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  3  1  1  3  1  1  3  1  1  3  1  1  3  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  3  1  1  3  1  1  3  1  1  3  1  1  3  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  3  1  1  3  1  1  3  1  1  3  1  1  3  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  3  1  1  1  1  1  1  1  1  1  3  1  1  1  7
    7  1  1  1  1  1  3  1  1  3  1  1  3  1  1  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    8  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  8
```

```
!2.1% assembly with AIC control rods
 module 2 2*19 1
    8  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  8
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  1  1  5  1  1  5  1  1  5  1  1  1  1  1  7
    7  1  1  1  5  1  1  1  1  1  1  1  1  1  5  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  5  1  1  5  1  1  5  1  1  5  1  1  5  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  5  1  1  5  1  1  3  1  1  5  1  1  5  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  5  1  1  5  1  1  5  1  1  5  1  1  5  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  5  1  1  1  1  1  1  1  1  1  5  1  1  1  7
    7  1  1  1  1  1  5  1  1  5  1  1  5  1  1  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    7  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  7
    8  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  8

!2.6% assembly with 20 pyrex rods
 module 3 2*19 1
    8  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  8
    7  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  7
    7  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  7
    7  2  2  2  2  2  4  2  2  4  2  2  4  2  2  2  2  2  7
    7  2  2  2  4  2  2  2  2  2  2  2  2  2  4  2  2  2  7
    7  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  7
    7  2  2  4  2  2  3  2  2  4  2  2  3  2  2  4  2  2  7
    7  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  7
    7  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  7
    7  2  2  4  2  2  4  2  2  3  2  2  4  2  2  4  2  2  7
    7  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  7
    7  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  7
    7  2  2  4  2  2  3  2  2  4  2  2  3  2  2  4  2  2  7
    7  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  7
    7  2  2  2  4  2  2  2  2  2  2  2  2  2  4  2  2  2  7
    7  2  2  2  2  2  4  2  2  4  2  2  4  2  2  2  2  2  7
    7  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  7
    7  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  2  7
    8  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  6  8

  lattice 1 2*1
   1

  lattice 2 2*1
   2

  lattice 3 2*1
   3

  assembly 1
   1

  assembly 2
   2

  assembly 3
   3
```

```
core 360
   1 3 1
   3 2 3
   1 3 1

XSEC
  addpath ../
  xslib ORNL declib60g02_e7.fmt

OPTION
  bound_cond 1 1 1 1 1 1
  solver 1 2
  ray 0.05 CHEBYSHEV-YAMAMOTO 16 2
  parallel 1 1 1 16
  conv_crit 2*1.e-5
  iter_lim 2000 2 3
  vis_edits T
  validation T C
.
```

APPENDIX D – PROBLEM 1 RESULTS

MPACT v1.0 Results for Problem 1 (Ref. 4):

Table D1: Problem 1 MPACT ENDF/B-VII Eigenvalue Results

		Eigenvalues					MPACT Eigenvalue Differences (pcm)			
Problem	**Description**	**KENO-VI CE**	**MCNP5 CE**	**PARAGON 6K**	**PARAGON 70g**	**MPACT 60g**	**KENO-VI CE**	**MCNP5 CE**	**PARAGON 6K**	**PARAGON 70g**
1A	565K	1.18761	1.18655			1.18634	**-127**	**-21**		
1B	600K	1.18294	1.18187			1.18120	**-174**	**-67**		
1C	900K	1.17239	1.17146			1.16958	**-281**	**-188**		
1D	1200K	1.16315	1.16313			1.16017	**-298**	**-296**		
1E	IFBA	0.77237	0.77125			0.77069	**-168**	**-56**		

KENO and MCNP uncertainties are ≤ 11 pcm . MCNP results are corrected from 600K per Ref. 4.

Table D2: Problem 1 MPACT ENDF/B-VI Eigenvalue Results

		Eigenvalues				MPACT Eigenvalue Differences (pcm)		
Problem	**Description**	**KENO-VI CE**	**PARAGON 6K**	**PARAGON 70g**	**MPACT 60g**	**KENO-VI CE**	**PARAGON 6K**	**PARAGON 70g**
1A	565K	1.18761			1.18634	**-127**		
1B	600K	1.18294			1.18120	**-174**		
1C	900K	1.17239			1.16958	**-281**		
1D	1200K	1.16315			1.16017	**-298**		
1E	IFBA	0.77237			0.77069	**-168**		

KENO and MCNP uncertainties are ≤ 11 pcm

APPENDIX E – MPACT CAPABILITY ASSESSMENT

Based on the application of MPACT v1.0 to AMA Problems 1 and 2 in this report, an assessment of code capability for these problems has been performed by AMA. The ratings used are below, and Table E1 provides the detailed assessment.

Table E1: Assessment of MPACT for Problems 1 and 2

				AMA Core Physics Problems	
#	**Type**	**R**	**Capability Description**	**1**	**2**
1	Devel	x	**Input based on reactor geometry, fuel enrichment, boron concentration, etc.**	1	1
2	Devel	x	**Calculate atomic number densities of each material composition**	2	2
3	Devel	x	**Automatically obtain fine-group microscopic cross sections for each mixture/material**	3	3
4	Devel	x	**Perform resonance self-shielding calculation for each unique fuel pin and material**	3	3
5	Devel		Perform cross section energy collapse based on local flux spectrum		
6	Devel	x	**Create transport mesh**	3	3
7	Devel		Perform properly weighted cross section homogenization for each mixed transport cell		
8	Devel		Account for thin absorber coatings such as IFBA and integral absorbers such as gadolinia	2	2
9	Devel	x	**Build and execute core simulator on target computer platform**	3	3
10	Devel	x	**Output eigenvalue**	3	3
11	Analy	x	**Validate eigenvalue against CE Monte Carlo calculations**	3	3
12	Devel		Account for spatial effects on cross sections		3
13	Devel		Account for spatial effects on energy collapse		
14	Devel		Provide parallelization for pin-by-pin cross section processing		
15	Devel	x	**Account for assembly gap**		2
16	Devel	x	**Permit reflective quarter symmetry**		1
17	Devel		Account for effects of prompt and delayed gammas on pin powers		0
18	Devel	x	**Output pin-by-pin relative reaction rates / power**		3
19	Devel	x	**Provide 2g flux and power distribution visualization**		1
20	Analy	x	**Validate pin powers against CE Monte Carlo calculations**		3
21	Analy	x	**Compare performance to NRC licenced and/or established industry code(s)**		3

AMA Assessment Level

0	Does not exist or does not work at this time
1	Development in process or implemented but with bugs or deficiencies
2	AMA Testing
3	AMA Accepted

	1	**2**
Development Status	83%	71%
Analysis Status	100%	100%
Total Status	**85%**	**76%**