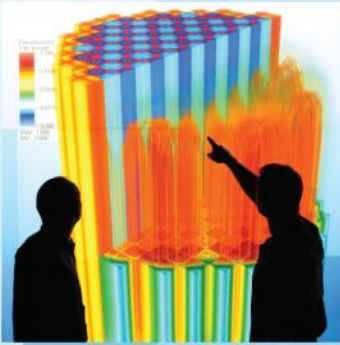Power uprates
and plant life extension
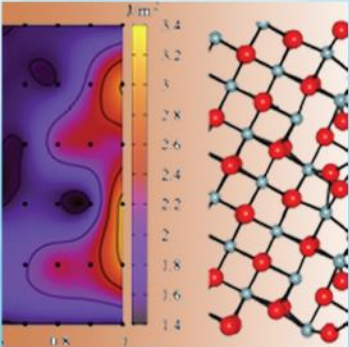
Engineering design
and analysis

Science-enabling
high performance
computing

Fundamental science

Plant operational data

CASL
Consortium for Advanced Simulation of LWRs

VERA Core Physics Benchmark Progression Problem Specifications

Revision 4
August 29, 2014

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Physics Integration

Oak Ridge National Laboratory

U.S. DEPARTMENT OF
ENERGY | Nuclear Energy

Oak Ridge National Laboratory

in partnership with

Electric Power Research Institute

Idaho National Laboratory

Los Alamos National Laboratory

Massachusetts Institute of Technology

North Carolina State University

Sandia National Laboratories

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REVISION LOG

Revision	Date	Affected Pages	Revision Description
0	8/31/2012	All	Original Release
1	12/21/2012	All	Modifications to Problem 1 and 2 specifications; Additional lattice cases added to Problem 2; addition of problems 4-2D, 5-2D, and REF1-2D to miscellaneous benchmarks
2	3/29/2013	All	Addition of Problem 5 and Problem 3B, and Problem 4 reference results. Modification of 1A, 2A, and 3A reference results.
3	3/31/2014	All	Addition of Problems 6-8. Updated all KENO results. Addition of measured data for Problem 5. Addition of more results and visualizations of previous problems. Added appendix for radial reflector sensitivity study.
4	8/29/2014	All	Addition of Problem 9-10. Updated Cycle 1 operating characteristics and added new IFBA and WABA lattice layouts.

Document pages that are:

Export Controlled __None_____

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EXECUTIVE SUMMARY

Provided are the detailed specifications for the VERA Core Physics Benchmark Progression Problems 1 through 10. These problems were selected to assist nuclear software and methods developers and analysts in progressing through capabilities needed to model U.S. nuclear power reactors and their operations. The problems provide a prioritization of the VERA requirements for the virtual reactor, beginning at the fuel pin level and progressing to full core, multi-physics, time-dependent problems. They also enable clear and concise communication about what capabilities have been achieved. In addition to the specifications, reference solutions are provided, if available, from a continuous energy Monte Carlo neutron transport solution.

Problems 1 to 9 represent geometries that are contained in the WBN1 initial startup core. Problems 5, 8, and 9 provide specification for models for which results can be directly compared to measured nuclear plant data. Cases which are not based on WBN1 are clearly identified. The data for these geometries is obtained from publicly available sources, and is described in common sections at the beginning of the document. Each of the benchmark problems uses variations of the same source of fuel data. Therefore, this document is publicly distributable.

Problem 5 provides measured data for the initial startup of WBN1 for reactor methods benchmarking purposes. This information has been released by TVA as part of CASL milestone L1:CASL.P7.01.

Problems 6-8 provide specification for coupled physics problems relating to startup and operation of a nuclear power reactor at operating conditions. References for these cases have not been generated, and the measured data is not yet available.

Problem 9 provides measured data for the operation of WBN1 throughout its entire first fuel cycle. Measured critical boron concentrations are provided to validate predicted reactivity and measured incore flux distributions will be provided in a later revision. Problem 9 provides gross confidence that the depletion of fuel and burnable absorbers is correct. This information has also been released publicly by TVA (through this document and other milestones).

Problem 10 provides the fuel assembly shuffle information for WBN1 Cycle 2, which supports simulation of the refueling outage between two fuel cycles. This completes the capability needed for multi-cycle steady-state simulation of U.S. PWRs.

CONTENTS

FIGURES

TABLES

ACRONYMS

2D	Two-Dimensional
3D	Three-Dimensional
AIC	Silver-Indium-Cadmium control rods
ARI	All Rods In
ARO	All Rods Out
B_4C	Boron Carbide control rods
BOC	Beginning-of-Cycle
BOL	Beginning-of-Life
CBW	Control Bank Reactivity Worth
CE	Continuous energy (as in cross sections)
CFD	Computational Fluid Dynamics
DBW	Differential Boron Reactivity Worth
DRW	Differential Control Rod Reactivity Worth
EFPD	Effective Full Power Day
EOC	End-of-Cycle
FP	Full Power
Gad	Gadolinia integral burnable absorber (Gd_2O_3)
GWd/MT	Gigawatt-day per metric ton (usually of Uranium)
HFP	Hot Full Power
HZP	Hot Zero Power
ITC	Isothermal Temperature Reactivity Coefficient
IFBA	Integral Fuel Burnable Absorber (here WEC's ZrB_2)
IRW	Integral Control Rod Reactivity Worth
LWR	Light Water Reactor
MG	Multi-group (as in cross sections)
NIST	National Institute of Standards and Technology
PCM	Percent milli (10^{-5})
PHI	Physics Integration Focus Area
PWR	Pressurized Water Reactor
RCCA	Rod Cluster Control Assembly
T/H	Thermal-Hydraulic
TVA	Tennessee Valley Authority
VERA	Virtual Environment for Reactor Applications
WABA	Wet Annular Burnable Absorber
WBN1	Watts Bar Nuclear Unit 1
WBN1C1	Watts Bar Nuclear Unit 1 Cycle 1
WEC	Westinghouse Electric Company
ZPPT	Zero Power Physics Tests

INTRODUCTION

The VERA Core Physics Benchmark Progression Problems (Figure 1) provide a method for developing and demonstrating increasing capabilities for reactor physics methods and software. They provide a model-based approach to prioritization of requirements, and create clear metrics to communicate development status. This document provides the detailed specification of the ten problems, ranging from a simple 2D pin cell to the full cycle depletion and refueling of a 3D reactor core configuration with control rods and burnable poisons consistent with actual nuclear power plant designs. All of the data in this document is publicly available and most of it is based on actual fuel and plant data from the initial core loading of Watts Bar Nuclear 1, a Westinghouse-designed 17x17 Pressurized Water Reactor (PWR) of the common vintage built in the U.S. in the 1980's and 1990's.

In addition to defining a common specification to test each level of capability, the document also provides reference solutions, when possible, based on continuous energy (CE) Monte Carlo methods using ENDF/B-VII.0 cross sections. This is important for the first five problems to define an analytical standard so that we can evaluate capability in context of accuracy. In some cases, ENDF/B-VI.8 cross sections are additionally used and these results are located in the appendices.

Each problem may be solved to different degrees of satisfaction. The section entitled "Capabilities" provides a list of many required or desired features of an excellent reactor analysis tool that could be demonstrated for each problem. It should be discouraged to approach these problems as "solved" or "not solved", but rather how well are they solved, with what ease, and how comprehensive is the software demonstrating the capabilities that are suggested. Regardless, successful progression through each problem will lead to a satisfactory benchmark against WBN1 Cycle 1.

Revision 1 of this document contains the following summary changes:

1. Corrected the UO_2 isotopics in reference input for Problems 1 and 2 (U-234 and U-238), worth approximately 80 pcm.
2. Changed the fuel density for Problems 1 and 2 to be consistent with the other problems
3. Added Problem 1E (IFBA pin cell)
4. Modified the Pyrex isotopics in reference input for Problem 2 to be more consistent with the material composition in the specification (i.e. changed from default SCALE material)
5. Added Problems 2K-2P (radially-zoned enrichment, IFBA, WABA, and Gadolinia)
6. Switched to development version of CE KENO-VI (SCALE 6.2 dev) for Problems 1 and 2.
   a. Captured improvements fix for $S(\alpha,\beta)$ fix (worth approximately 100 pcm for UO_2)
   b. Enabled output of region- based fission rate tallies (rather than nu-fission)
   c. Provided parallel (MPI) version for execution on multiple cores, permitting much larger numbers of particles, resulting in lower eigenvalue and reaction rate distribution uncertainties.
7. Modified CE KENO-VI post-processing technique to take credit for octant symmetric fuel rods in the calculation of fission rate distribution uncertainties (Problem 2).
8. Added new 2D problems for 3x3, quarter core, and a simple reflector case (new section "Miscellaneous Benchmarks")
9. Added appendices of reference input and results for Problems 1 and 2 for access and convenience of the reader.

Revision 2 of this document contains the following summary changes:

1. Modified Problem 1A and 2A reference solutions with actual 565K CE results.
2. Added Problem 2Q, a 2D lattice solution which includes spacer grid material.
3. Modified Problem 3A results with new CE KENO-VI development version, as described in the Revision 1 changes (Item 6).
4. Added Problem 3B.
5. Added CE KENO-VI results for Problem 4, including pin powers and control rod reactivity worths.
6. Added the Problem 5 specification with CE KENO-VI results for criticality, control bank reactivity worths, and other reactivity coefficients.

Revision 3 of this document contains the following summary changes:

1. Added the density of carbon steel.
2. Added more operating parameters and references.
3. Regenerated all CE KENO-VI reference results with latest SCALE 6.2 Beta release using the INL supercomputer Fission to achieve many more particles and thus lower power distribution uncertainties.
4. Added correction factors for all 565K KENO cases to account for the lack of temperature-dependent H-1 scattering data ($S(\alpha,\beta)$).
5. Added Problem 4C-2D, a 2D 3x3 assembly case with B_4C control rods.
6. Added Problem 5C-2D, a 2D quarter-core case with B_4C control rods.
7. Changed the temperature of Problem 5-2D to 565K.
8. Revised the Problem 5 specification for consistency with actual WBN1 ZPPT tests, and added measured results. Also added improved ITC predictions and Bank D integral rod worths.
9. Added Problems 6-8 initial specifications, without reference solutions. Efforts are ongoing to create these references for future revisions.
10. Added results for 565K versions of Problem 4-2D.
11. Added results of a radial reflector sensitivity study based on Problem 5A-2D in the appendices, including quantification of the effect of the core barrel, neutron pads, and vessel.
12. Added more results and visualizations for the larger problems.

Revision 4 of this document contains the following summary changes:

1. Addition of initial specifications for Problems 9 and 10.
2. Updated core operating characteristics based on data obtained from TVA for Problem 9.
3. Added new IFBA and WABA lattice arrangements based on publicly available data.
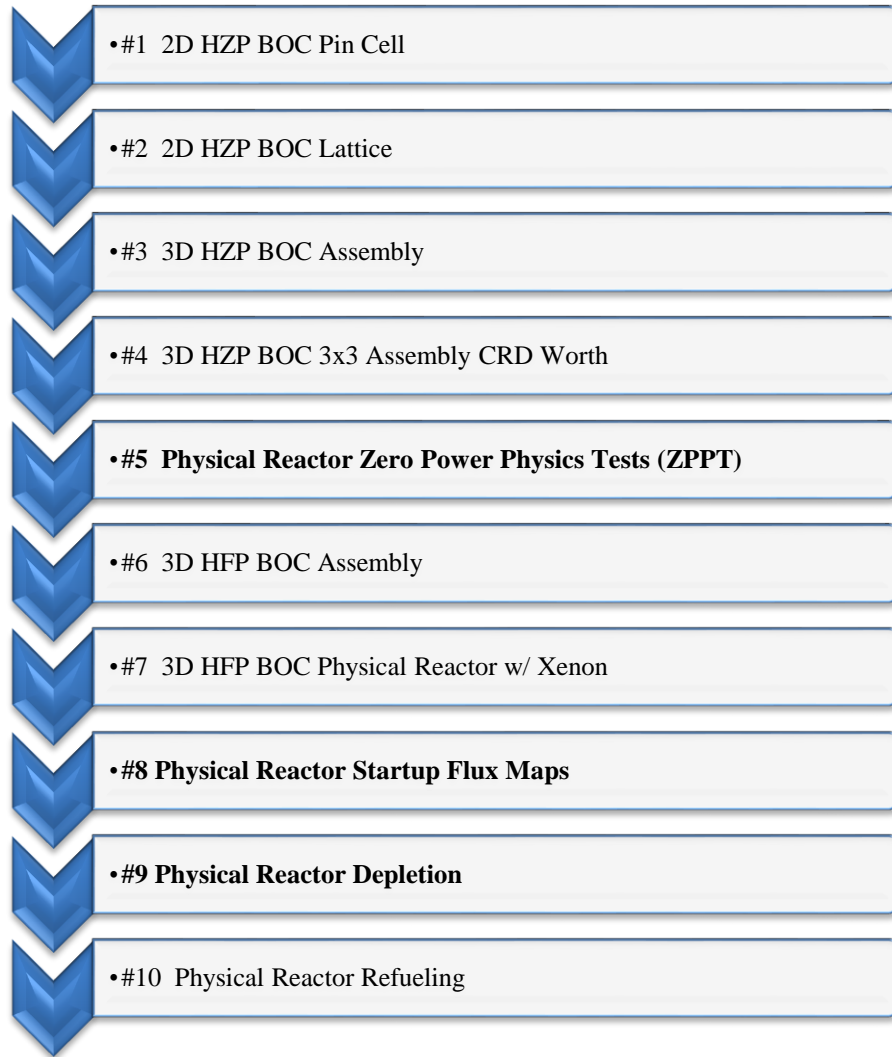
* **Bold** indicates comparisons against measured data

Figure 1: Ten VERA Core Physics Benchmark Progression Problems

This document contains specifications for all ten problems, but measured data is not yet available or releasable in all cases.   Reference solutions are included for each problem as are available and feasible to generate. In addition, as VERA development has progressed, additional test cases have been created that do not explicitly fit into the progression of these problems, so those are documented separately in section "Miscellaneous Benchmarks". Most important of these are the 2D 3x3 cases (4-2D) and the 2D quarter-core cases (5-2D), which provide reference Monte Carlo distributions with very low statistical uncertainty.

1. GEOMETRY

Each of the problems in this specification is based on actual fuel and core geometries used in the Watts Bar Nuclear 1 (WBN1) initial core loading. The fuel is a Westinghouse 17x17 design utilizing discrete Pyrex burnable poisons and hybrid AIC/B$_4$C rod cluster control assemblies (RCCAs). This section describes the general dimensions and material content of this fuel which will be applicable to each progression problem. The specifications are obtained from publicly available sources for WBN1 or similar power plant designs. All input is provided at cold conditions. In a few cases (Problems 2K-2P), the fuel or poison specification is not based on WBN1, but is similar to other common PWR fuel designs.

1.1 FUEL ROD GEOMETRY

The 17x17 fuel rod geometry is consistent for all fuel in the WBN1 core. It contains a 12' axially-uniform UO$_2$ fuel stack contained within Zircaloy-4 cladding, with an upper gas plenum, plenum spring, and upper and lower end plugs. Figure 2 below presents the fuel rod geometry. Table 1 provides the detailed rod data as is possible from the source.
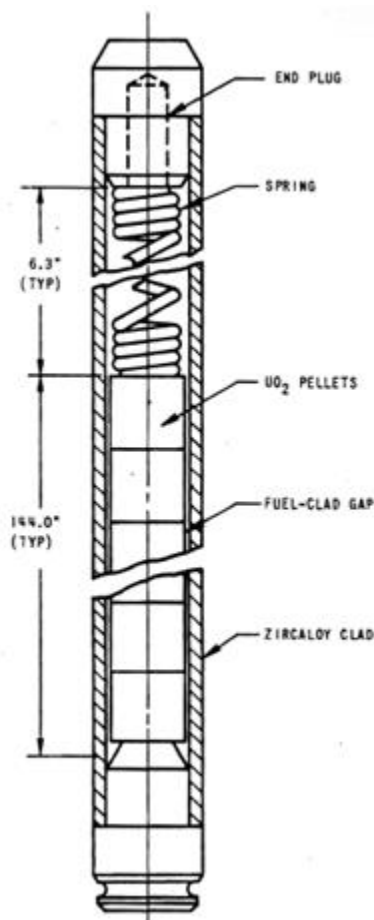
Figure 2: Fuel Rod Arrangement
(Ref. 1 Figure 4.2-3, in inches)
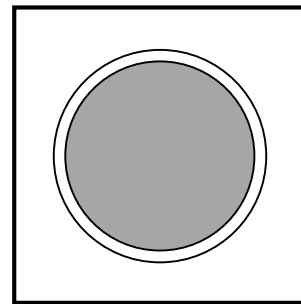
Table 1: Fuel Rod Specification (Ref. 1)

Input	Value
Pellet Radius	0.4096 cm
Inner Clad Radius	0.418 cm
Outer Clad Radius	0.475 cm
Rod Pitch	1.26 cm
Rod Height	385.1 cm
Fuel Stack Height	365.76 cm
Plenum Height	16.0 cm
End Plug Heights (x2)	1.67 cm
Pellet Material	UO$_2$
Clad / Plugs Material	Zircaloy-4
Plenum Spring Material	Stainless Steel
Fill Gas Material	Helium

- The end plugs are assumed to be the same height. The volume, mass, chamfer, etc. for the plugs are unknown.
- The volume or mass of the plenum spring is not included in this specification.

1.2 FUEL ROD AND GUIDE TUBE LAYOUT (LATTICE)

Each 17x17 assembly contains 24 guide tubes (or thimbles) serving as structure and as a location for discrete inserts such as rod cluster control assembly (RCCA) rodlets or discrete burnable poison rods. There is also one instrument tube at the lattice center for insertion of an incore neutron flux detector. Each of these tubes is Zircaloy-4 and, other than the instrument tube, connects the top and bottom nozzles. These tubes are arranged in a fixed radial layout for all assemblies, shown in Figure 3. Table 2 provides the detailed guide tube and instrument tube specifications. The guide tube dashpot is ignored. In addition, a small inter-assembly gap exists between all assemblies containing the core moderator.

IT Instrument Tube

GT RCCA / Burnable Poison / Thimble Plug Guide Tube
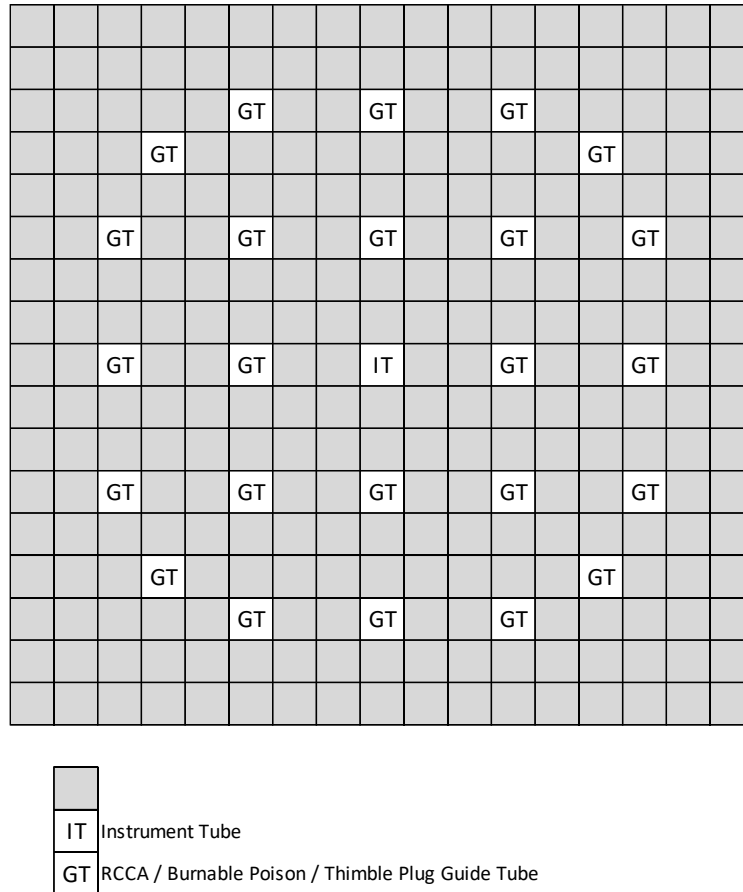
Figure 3: 17x17 Lattice Fuel Rod and Thimble Arrangement
(Ref. 1 Figure 4.2-1)

Table 2: 17x17 Lattice Specification (Ref. 1)

Input	Value
Inner Guide Tube Radius	0.561 cm
Outer Guide Tube Radius	0.602 cm
Inner Instrument Tube Radius	0.559 cm
Outer Instrument Tube Radius	0.605 cm
Tube Materials	Zircaloy-4
Rod Pitch	1.26 cm
Assembly Pitch	21.50 cm
Inter-Assembly Half Gap	0.04 cm

1.3 SPACER GRIDS

Each 17x17 assembly in WBN1 contains six intermediate spacer grids and two end grids which provide lateral structure support, reduction in rod vibration and bow, and in some cases coolant flow mixing. The intermediate grids are located in the active fuel region and are made of Zircaloy-4 to limit neutron absorption. However, the end grids are located at the end or outside of the fuel stack and are predominately made of Inconel for improved structural support.

The majority of each spacer grid is comprised of an orthogonal array of thin straps, each with a mechanism for rod contact (dimples, springs). In addition, each grid also includes a set of spacer sleeves that contact the guide tubes and instrument tube and limit the axial movement of the grids. These sleeves are not necessarily made from the same material as the straps. None of the reference solutions in this specification include the spacer sleeves.

The spacer grid data needed for neutronics calculations is simply the mass and volume of each material and the axial location of each grid. It has been shown that detailed models, such as CAD models or drawings, of spacer grids are not required for accurate reactivity and pin power calculations. Additional information will be needed for sub-channel or CFD analyses of the grids.

Complete public grid data for WBN1 has not been located. The specification below in Table 3 is partially based on approximations from other plant data (Ref. 8) and other grid types. Note that all axial elevations in this document are relative to the fuel assembly seating surface, which coincides with the top of the lower core plate.

Table 3: Spacer Grid Specification

	End Grids	Intermediate Grids
Number	2	6
Material	Inconel-718	Zircaloy-4
Mass (g)	1017	875
Height (cm)	3.866	3.810
Mixing Vanes ?	No	Yes
Axial Locations (cm) (center of inner strap relative to top of lower core plate)	13.884 388.2	75.2 127.4 179.6 231.8 284.0 336.2

- The spacer grid types, heights, and locations are obtained from Reference 1 (shown in Figure 4). For simplicity, the lower end grid has been shifted slightly up to align with the bottom of the fuel stack.
- The spacer grid masses are estimated from a total mass given in Reference 1, distributed based on volume fractions obtained from Reference 8 (based on OFA values scaled to the V5H inner strap height).
- The spacer grid sleeve data is not included in this specification and can be ignored.
- The axial location of the bottom end grid is shifted slightly to align with the bottom of the fuel stack. The public data is inconsistent and questionable in this area and aligning the grid with the fuel simplifies the modeling.

1.4 ASSEMBLY GEOMETRY

Each Westinghouse 17x17 assembly in WBN1 is comprised of fuel rods, guide and instrument tubes, spacer grids, and top and bottom nozzles. Figure 4 demonstrates the axial assembly geometry. The specifications for the assembly are provided in Table 4 and specifications for the nozzles and core plates are given in Table 5.

Table 4: Fuel Assembly Specification (Ref. 1)

Input	Value
Assembly Pitch	21.50 cm
Inter-Assembly Half Gap	0.04 cm
Total Assembly Height	406.337 cm
Bottom Nozzle Height	6.053 cm
Top Nozzle Height	8.827 cm
Fuel Rod Height	385.1 cm
Axial Location of Fuel Stack	11.951 cm
Lower Gap Height (above bottom nozzle)	4.228 cm
Upper Shoulder Gap Height (below top nozzle)	2.129 cm
UO_2 Mass	522.0 kg

- The dashpot region of the guide tubes is not included in this specification.

Figure 4: Axial Fuel Assembly Arrangement
(Ref. 1 Figure 4.2-2, in inches)

Table 5: Assembly Nozzle and Core Plate Specification

	Bottom Nozzle	Top Nozzle	Lower Core Plate	Upper Core plate
Material	SS-304	SS-304	SS-304	SS-304
Mass (kg)	6.25	6.25	---	---
Height (cm)	6.053	8.827	5.0	7.6
Volume Fraction (%)	---	---	50%	50%
Axial Location (cm) (relative to top of lower core plate)	0.0	397.51	-5	406.337

- The nozzle and core plate materials, heights, and axial locations are obtained from Ref. 1.
- The lower core plate thickness is obtained from Reference 9 for a generic Westinghouse plant.
- The upper core plate thickness is assumed. The model should be insensitive to this value.
- The nozzle masses are assumed to be equal, with an approximate total mass of 12.5 kg. It is assumed that the model is insensitive to these values because of the distance to the fuel.
- The upper and lower core plates are perforated with flow holes which allow the coolant to enter and exit the fuel assemblies. Because these plates are located a large distance from fuel, it is sufficient to assume a 50% volume fraction of the stainless steel and coolant.

1.5 PYREX GEOMETRY

The initial WBN1 core loading utilizes various patterns of the Pyrex (borosilicate glass, B_2O_3-SiO_2) discrete burnable neutron absorber located in the assembly guide tubes. These inserts may be placed in any assembly which is not located in a RCCA location, using several possible radial configurations shown in Figure 5. The specification for Pyrex is provided below, based on data from References 1 and 8.

Table 6: Pyrex Rod Specification

Input	Value
Enrichment	12.5 wt% B_2O_3
Boron-10 Loading	6.24 mg/cm
Pyrex Density	2.25 g/cc
Inner Tube Inner Radius	0.214 cm
Inner Tube Outer Radius	0.231 cm
Pyrex Inner Radius	0.241 cm
Pyrex Outer Radius	0.427 cm
Cladding Inner Radius	0.437 cm
Cladding Outer Radius	0.484 cm
Poison Height	360.68 cm
Plenum Height above Poison	22.2 cm
Axial Location of Poison	15.761 cm
End Plug Height	≈ 2.54 cm
Inner Tube Material	SS304
Plenum Material	Helium
Cladding Material	SS304
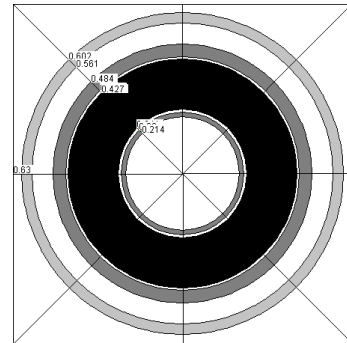
The Pyrex isotopic weight fractions are calculated based on 12.5% B_2O_3 weight percent (Ref. 1) and atomic masses obtained from NIST (www.nist.gov). These values are provided in the table below. For example, the mass fraction of B-10 in B_2O_3-SiO_2, assuming natural 19.8 at% B-10 in boron, is calculated as the following:

$$f_{B10} = 0.125 \times \frac{2 \times 10.811}{2 \times 10.811 + 3 \times 15.9994} \times \left(\frac{10.012937 \times 0.198}{10.012937 \times 0.198 + 11.009305 \times 0.802} \right) = \mathbf{0.712}\%$$

It is noted that standard Pyrex contains trace amounts of other compounds such as Na_2O, Al_2O_3, Fe_2O_3, CaO, MgO, and Cl. These are ignored here as only the boron-10 containing compounds will affect the neutron flux significantly.

Table 7: Pyrex Isotopics

Isotope	Weight Fraction (%)
B-10	0.712
B-11	3.170
O-16	55.217
Si	40.901

The density required to obtain the specified linear loading of B-10 can be simply calculated using the area of the annular poison tube.

$$\rho_{pyrex} = 0.00624 \; \frac{g \; B10}{cm} \times \frac{1}{\pi \times (0.427^2 - 0.241^2)cm^2} \times \frac{g \; pyrex}{0.00712 \; g \; B10} = 2.25 \; {}^g/_{cc}$$
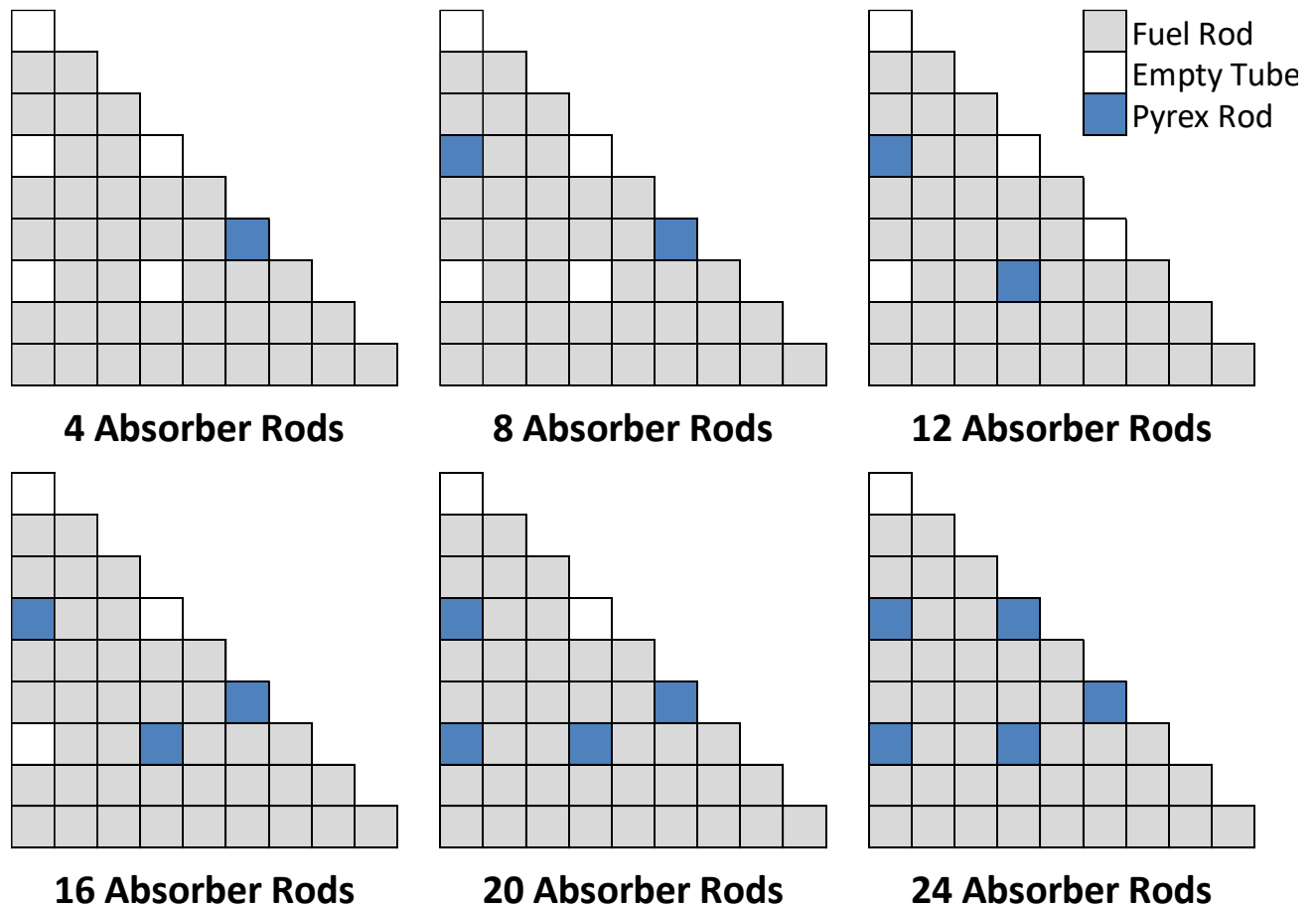
Figure 5: Burnable Absorber Rodlet Configurations (Octant Symmetry)
(Ref. 1 Figure 4.3-4, and Ref. 21 Figure 12)

1.6 CONTROL ROD GEOMETRY

WBN1C1 utilized hybrid B$_4$C RCCAs with AIC tips. These rods are inserted into each guide tube of any assembly in a controlled core location. The specification of these rods, their axial location, and movement characteristics are described below. These values are estimates for WBN1 and were compiled from various sources including Refs. 1, 8, and 10.
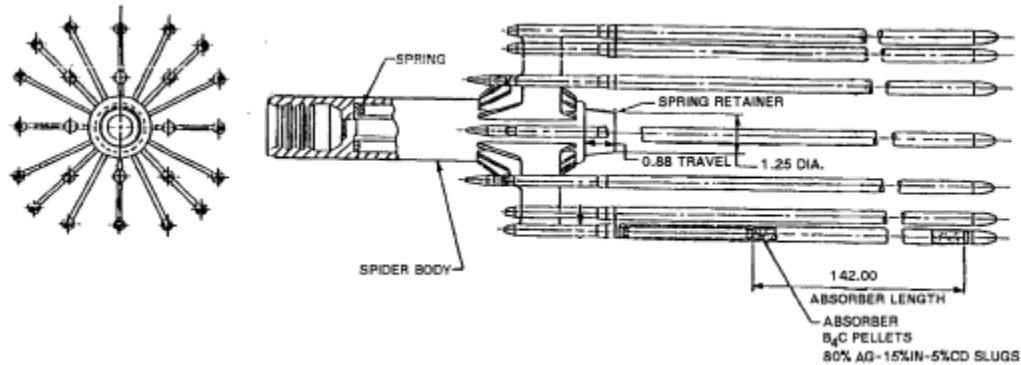
Figure 6: RCCA Assembly
(Ref. 1 Figure 4.2-15, in inches)

Table 8: RCCA Rod and Drive Specification

Input	AIC	B$_4$C
Composition	80/15/5% Ag/In/Cd (Lower)	100% B$_4$C (Upper)
Poison Density	10.2 g/cc	1.76 g/cc
Poison Radius	0.382 cm	0.373 cm
Poison Height	101.6 cm	259.08 cm
Cladding Inner Radius	0.386 cm	
Cladding Outer Radius	0.484 cm	
Total Poison Height	360.68 cm	
Axial Location of Poison (when fully inserted)	17.031 cm	
Plenum Height above Poison	10.7 cm	
End Plug Height	≈ 1.9 cm	
Step Size	1.5875 cm	
Maximum number of steps	230	
Cladding Material	SS304	
Plenum Material	Helium	
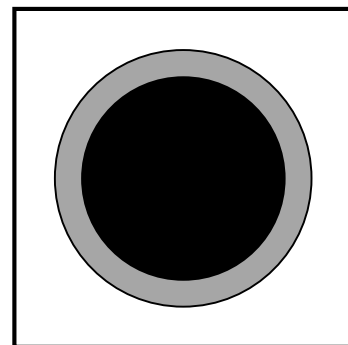
1.7 THIMBLE PLUG GEOMETRY

Thimble plugs are used to prevent excess bypass flow through guide tubes that do not contain discrete burnable poison rods or RCCA rodlets. These are not typically modeled because the plugs are fairly short and do not extend into the active fuel region. This data was obtained from Reference 1 and Reference 8. The end caps are ignored.

Table 9: Thimble Plug Specification

Input	Value
Material	SS304
Outer Radius	0.538 cm
Height	11.0 cm
Axial Location	383.31 cm

1.8 INSTRUMENT THIMBLE GEOMETRY

Instrument tube thimbles are inserted into an assembly's instrument tube from below the reactor core to guide the movable incore instrument through the center of an assembly. These thimbles are thick stainless steel annular tubes which serve as reactor core pressure boundaries, displacing core moderator. Reference 1 and Reference 11 provide reasonable values for this specification.

Table 10: Instrument Thimble Specification

Input	Value
Material	SS304
Inner Radius	0.258 cm
Outer Radius	0.382 cm
Height	Same as instrument tube
Inner Material	Vacuum
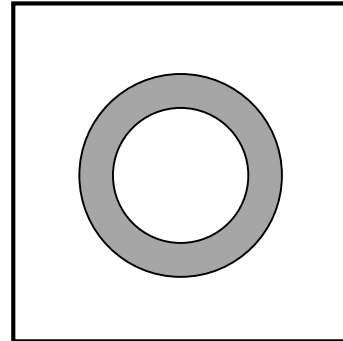
- The top of the instrument thimble is unknown. It is located somewhere between the top of the active fuel and the top nozzle. It is assumed here that the height is the same as the instrument tube, which is assumed to extend up to the top nozzle.

1.9 INTEGRAL FUEL BURNABLE ABSORBERS (IFBA)

Use of IFBA is a common modern technique for optimized fuel assembly reactivity control and power distribution management. It is a very thin ZrB_2 coating on selected UO_2 fuel pellets in an assembly. Because the boron is completely depleted quickly, and it does not displace fuel material, there is no residual reactivity penalty. Though IFBA is not used in WBN1 Cycle 1, it is included in these specifications because of its extensive use in modern PWR fuel and because it is somewhat challenging for nuclear methods and software (and it is used in WBN1 Cycle 2). The IFBA specs below are obtained predominately from Reference 12.

Table 11: IFBA Fuel Rod Specification

Input	Value
Poison Material	ZrB_2
Boron-10 Loading	2.355 mg/in
Boron-10 Enrichment	50%
Coating Thickness	10 μm
Coating Density	3.85 g/cc
Poison Height	304.8 cm
Poison Location	Centered axially

- Other than the ZrB_2 coating, the IFBA rod geometry is the same as provided in Table 1
- The material, loading, and height are provided in Reference 12
- The boron enrichment is assumed based on non-proprietary communication with CASL core partners. The results are insensitive to the actual enrichment as long as the boron-10 loading is preserved.
- Publicly available data refers to IFBA thicknesses of 5 to 15 μm. In this case, 10 μm is used as an approximate, and easy to use, value. The results are insensitive to the actual thickness as long as the boron-10 loading is preserved.
- The coating density is calculated below based on the fuel pellet diameter, coating thickness, and boron-10 loading.

The IFBA isotopic weight fractions are calculated based on the values in the table above and atomic masses obtained from NIST. For example, the mass fraction of B-10, assuming 50% B-10 enrichment, is calculated as the following:

$$MW_B = 1 \Big/ \left(\frac{0.5}{10.012937} + \frac{0.5}{11.0093054} \right) = 10.4875 \ g/mol$$

$$f_{B10,B11} = 50\% \times \frac{2 \times 10.4875}{91.224 + 2 \times 10.4875} = \mathbf{9.347\%}$$

The density required to obtain the specified linear loading of B-10 can be simply calculated using the area of the coating based on the fuel rod geometry in Section 1.1.

$$\rho_{ifba} = 2.355 \ \frac{mg \ B10}{in} \times \frac{1 \ in}{2.54 \ cm} \times \frac{1 \ g}{10^3 \ mg} \times \frac{1}{\pi \times (0.4106^2 - 0.4096^2) \ cm^2} \times \frac{g \ ifba}{0.09347 \ g \ B10}$$

$$= \mathbf{3.85} \ \mathbf{{}^g\!/\!_{cc}}$$

Alternately, the isotopic densities in units of atoms/bn-cm are provided in Table 12. The radial arrangements of the IFBA rods used in this document are shown in Figure 7.

Table 12: IFBA Isotopics

Isotope	Weight Fraction (%)	Atom Density (/bn-cm)
B-10	9.347	2.16410E-02
B-11	9.347	1.96824E-02
Zr	81.306	2.06617E-02

48 IFBA (Ref. 22)   80 IFBA (Ref. 12)

104 IFBA (Ref. 13)   128 IFBA (Ref. 14)
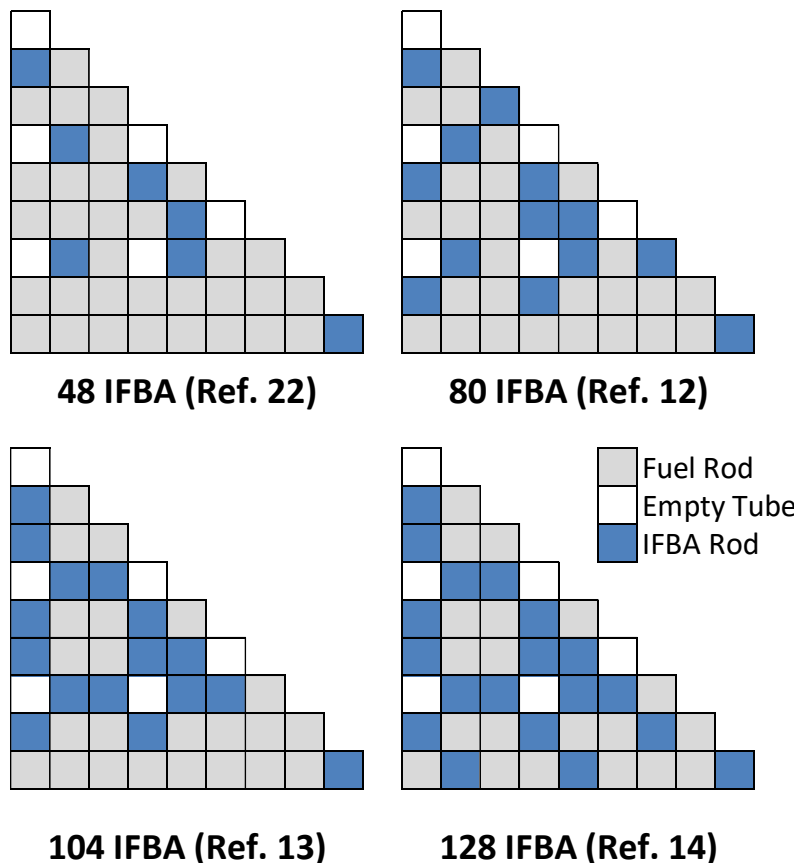
Figure 7: IFBA Configurations (Octant Symmetry)

1.10 WET ANNULAR BURNABLE ABSORBERS (WABA)

WABA rods are a common discrete burnable poison utilized within the guide tubes of modern Westinghouse fuel. Its annular design permits more neutron moderation at end-of-cycle, reduced neutron absorption, and more complete absorber depletion (Ref. 12). Though WABA is not used in WBN1 Cycle 1, it is included in these specifications because of its extensive use in modern PWR fuel and because it is often used in combination with IFBA fuel (and it is used in WBN1 Cycle 2). The WABA specs below are obtained from Reference 13.

Table 13: WABA Rod Specification

Input	Value
Poison Material	$B_4C-Al_2O_3$
Boron-10 Loading	6.03 mg/cm
Poison Density	3.65 g/cc
Inner Clad Inner Radius	0.286 cm
Inner Clad Outer Radius	0.339 cm
Poison Inner Radius	0.353 cm
Poison Outer Radius	0.404 cm
Cladding Inner Radius	0.418 cm
Cladding Outer Radius	0.484 cm
Annulus Material	Moderator
Cladding Material	Zircaloy-4
Plenum/Gap Material	Helium
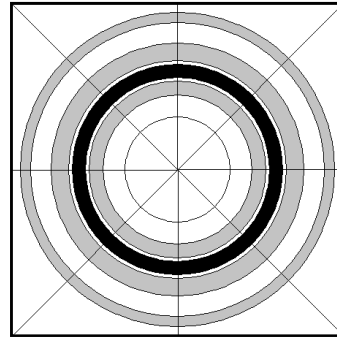
The WABA isotopic weight fractions are calculated based on the provided B-10 loading and poison density from Reference 13, and atomic masses obtained from NIST. These values are provided in the table below. For example, the mass fraction of B-10 of $B_4C-Al_2O_3$ is calculated as the following:

$$f_{B10} = \frac{\frac{0.00603\ g_{B10}}{cm}\ g \times \frac{1}{\pi \times (0.404^2 - 0.353^2)\ cm^2}}{3.65\ ^g/_{cm^3}} = \mathbf{1.362\%}$$

The other B_4C isotopics are computed based on the natural composition of boron, and natural Al_2O_3 is used to fill the balance of the mixture.

Table 14: WABA Isotopics

Isotope	Weight Fraction (%)	Atom Density (/bn-cm)
B-10	1.36	2.99014E-03
B-11	6.07	1.21116E-02
C	2.06	3.77542E-03
Al	47.90	3.90237E-02
O-16	42.61	5.85355E-02

WABA radial configurations (lattice arrangements) are the same as that of Pyrex shown in Figure 5. The 20 WABA layout is the same as shown in Reference 13. The 4 and 8 layouts are provided in Reference 20 (Figure 4).

1.11 GADOLINIA INTEGRAL BURNABLE ABSORBER

Gadolinia, or gadolinium oxide, Gd_2O_3, has also been utilized successfully for many decades in LWR fuel assemblies. Gadolinia is mixed homogeneously within the UO_2 fuel pellets for a few select rods in the assembly in predetermined concentrations usually ranging from 2-8% by weight. In addition, fuel rods containing gadolinia are usually lower enriched in U-235 than non-poison rods in the same assembly for economic concerns and to ensure sufficient safety margins. Though gadolinia is not used in WBN1 Cycle 1, nor is it typically used in assemblies manufactured by Westinghouse, it is included in these specifications because of its extensive use in other LWR fuel and because its very high neutron absorption cross section creates radial heterogeneities that can be very challenging for reactor physics methods. The gadolinia specs below are obtained from Reference 15.

Table 15: Gadolinia Fuel Rod Specification

Input	Value
Poison Material	Gd_2O_3
Gadolinia Concentration	5%
Fuel Density	10.111 g/cc

- Other than the fuel composition, the gadolinia rod geometry is the same as provided in Table 1.
- The fuel density for the mixed gadolinia rod is assumed to be based on the corresponding weight fractions of each component. With a gadolinia density of approximately 7.407 g/cc (www.wikipedia.com), the fuel pellet density can be approximated as

$$(7.407 * 0.05 + 10.36 * 0.95) \times \frac{10.257}{10.36} = \mathbf{10.111\ g/cc}$$

where the ratio 10.257/10.36 accounts for the fraction of the ideal cylindrical fuel volume that is lost in the pellet dishes and chamfers as described in section 2.2. The gadolinia radial layouts used in this specification are provided in Figure 8.

12 Gad   **24 Gad**
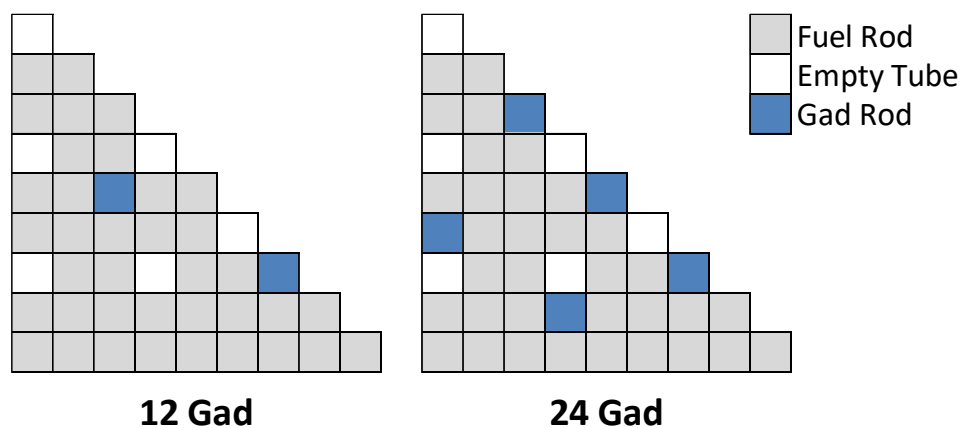
Figure 8: Gadolinia Configurations (Octant Symmetry)
(Ref. 15 p. 40)

1.12 REACTOR CORE LOADING CONFIGURATION

The core loading pattern refers to the radial placements of fuel assemblies, discrete burnable absorbers, control rod types and bank definitions, and incore instruments. For most of the problems in this specification, the configuration used by WBN1 for its initial Cycle 1 startup is used. This configuration is publically available from data sources such as Reference 1.

Figure 9 provides the radial core layout of fuel assemblies and poison configurations for the core loading. There are three regions of fuel assemblies which are of the type defined in sections 1.1-1.5 but have specific enrichments of 2.11%, 2.619%, and 3.10%, as defined by Section 2.1. The discrete poisons are Pyrex rods specified by the number of rods in the assembly, shown in Figure 5.

The figure does not specify locations of thimble plugs, per Section 1.7, but it should be assumed that every assembly guide tube in the core will contain a discrete burnable poison, a RCCA rodlet, or a thimble plug.

	H	G	F	E	D	C	B	A
8	2.1	2.6 / 20	2.1	2.6 / 20	2.1	2.6 / 20	2.1	3.1 / 12
9	2.6 / 20	2.1	2.6 / 24	2.1	2.6 / 20	2.1	3.1 / 24	3.1
10	2.1	2.6 / 24	2.1	2.6 / 20	2.1	2.6 / 16	2.1	3.1 / 8
11	2.6 / 20	2.1	2.6 / 20	2.1	2.6 / 20	2.1	3.1 / 16	3.1
12	2.1	2.6 / 20	2.1	2.6 / 20	2.6	2.6 / 24	3.1	
13	2.6 / 20	2.1	2.6 / 16	2.1	2.6 / 24	3.1 / 12	3.1	
14	2.1	3.1 / 24	2.1	3.1 / 16	3.1	3.1		
15	3.1 / 12	3.1	3.1 / 8	3.1	Enrichment / Number of Pyrex Rods			

Figure 9: Core Fuel and Poison Loading Pattern (Quarter Symmetry)
(Ref. 1 Figures 4.3-1 & 4.3-5)

Figure 10 provides the radial core layout of RCCAs. All of the control rods are hybrid B$_4$C with AIC tips as described in Section 1.6. Any fuel assembly which is in a RCCA location may not have a discrete burnable poison and will have all 24 guide tubes containing RCCA rodlets. In the operation of the reactor, the RCCAs are moved in groups, called "banks". The bank labels are shown by location in Figure 10. The shutdown banks, beginning with "S", are used only for safety shutdown and not during operation. Bank D is the primary regulating bank for reaching and maintaining criticality during operation, so this bank is often used in the benchmark problems.

Note that the RCCA shutdown banks SC and SD are not octant symmetric. This requires either full or rotational quarter symmetry for an accurate solution.

	H	G	F	E	D	C	B	A
8	D		A		D		C	
9						SB		
10	A		C				B	
11				A		SC		
12	D				D		SA	
13		SB		SD				
14	C		B		SA			
15								
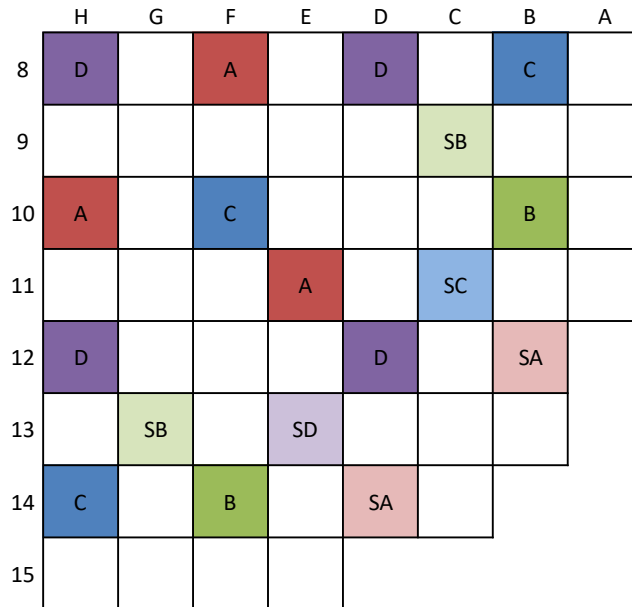
Figure 10: Core RCCA Bank Positions (in quarter symmetry)

(Ref. 1 Figure 4.3-36)

Figure 11 provides the incore instrumentation locations in the core. In each of these locations a hollow thimble tube, which provides a path for the movable incore detector system, is placed in the center instrument tube in the assembly. Since the tube does not contain moderator, there is a significant neutronic effect on the adjacent pin powers. The instrument thimble is described in Section 1.8.

Note that there are 58 instrument locations and their locations are not symmetric.

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							D			D					
2		D			D			D							
3								D		D		D		D	
4		D	D					D							
5					D			D		D		D			
6	D		D			D		D						D	
7				D			D		D			D			
8	D		D		D		D		D		D	D	D		
9		D						D		D					D
10					D		D					D			
11	D				D			D		D					D
12						D		D				D			
13			D		D			D						D	
14			D				D		D		D				
15					D		D								
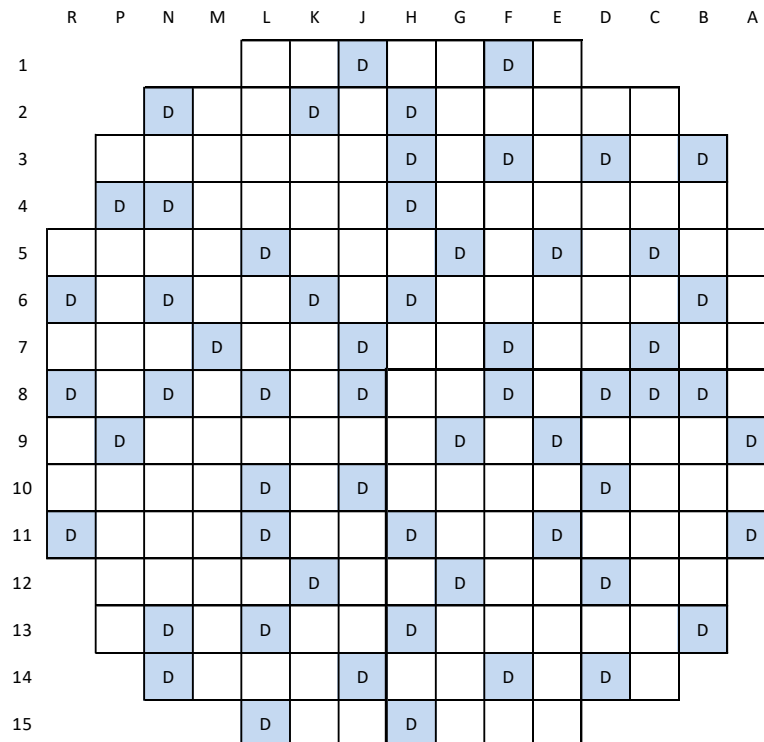
Figure 11: Core Incore Instrumentation Locations

(Ref. 1 Figure 4.4-22)

1.13 RADIAL CORE AND VESSEL GEOMETRY

The nuclear fuel assemblies are arranged in a cylindrical array to form the reactor core. The core is surrounded by baffle plates (also called a core liner), and contained within the core barrel and the reactor vessel itself. Table 4.1-1 of Reference 1 provides a comparison of the WBN1 core structure to that of McGuire Nuclear Station (MNS). The specifications for the core structure for MNS are described in Reference 8, which is used to provide the data below.
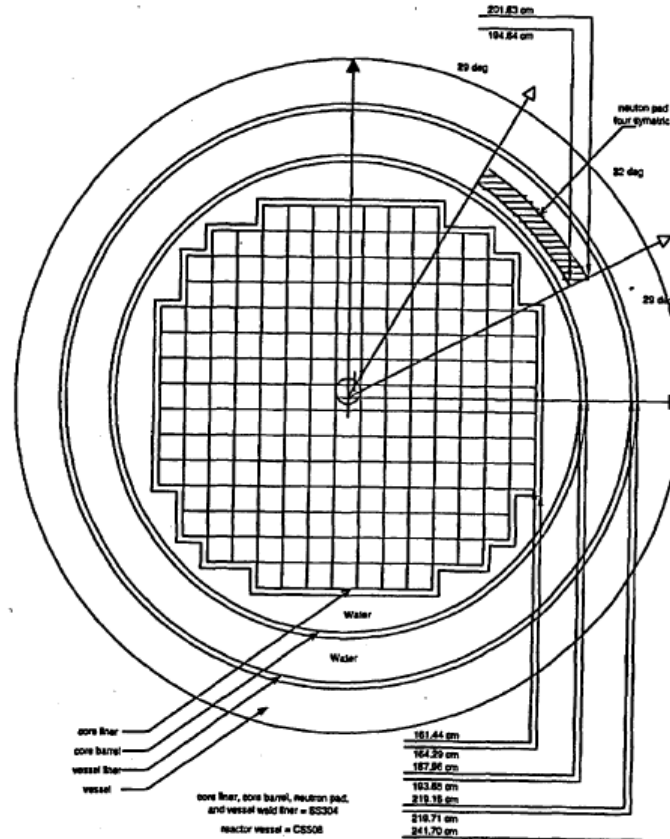
Figure 12: Radial Core Structure
(Ref. 8 Figure 2.1)

Table 16: Core Structure Specification (Ref. 8)

Structure	Input	Value
Baffle	Material	SS304
	Thickness	2.85 cm
	Gap between Fuel and Baffle	0.19 cm
Barrel	Material	SS304
	Inner Radius	187.96 cm
	Outer Radius	193.68 cm
Neutron Pad	Material	SS304
	Inner Radius	194.64 cm
	Outer Radius	201.63 cm
	Arc Length	32°
	Angular Location	45°
	Height	365.76 cm
Vessel	Liner Material	SS304
	Liner Inner Radius	219.15 cm
	Material	CS508
	Inner Radius	219.71 cm
	Outer Radius	241.70 cm

2. MATERIALS

This section supplies the default material properties for the progression problems based on the initial WBN1 core.

- The default density for Zircaloy-4 is **6.56 g/cc** (Ref. 3)
- The default density for Stainless Steel 304 is **8.00 g/cc** (Ref. 3)
- The default density for Inconel-718 is **8.19 g/cc** (Ref. 3)
- The default density for Carbon Steel is **7.85 g/cc** (Ref. 3)
- The moderator density for the WBN1 core at hot-zero-power (HZP) conditions is **0.743 g/cc** based on conditions of 565K and 2250 psi (Ref. 4)

2.1 FUEL ENRICHMENT

There are three regions in the WBN1 initial core loading pattern, with as-built enrichments of **2.11**, **2.619**, and **3.10** (Ref. 2). The fuel isotopics may be determined based on the following equations using the U-235 enrichment (weight <u>percent</u>), w (Ref. 5):

Table 17: Example LEU Isotopic Equations

Isotope	Equation
U-234	$0.007731 \times w^{1.0837}$
U-235	W
U-236	$0.0046 \times w$
U-238	Balance

In addition to these enrichments for WBN1, additional values are used for some problems for instances of radial zoning and use of gadolinia.

2.2 FUEL DENSITY

The fuel pellet density is listed in Reference 1 as 94.5% of theoretical (10.96 g/cc), which is **10.36 g/cc**. However, this density does not account for pellet dishes and chamfers, which reduce the overall fuel volume for the same pellet stack height. Therefore, for problems using an ideal cylindrical approximation of the fuel pellets, the effective pellet density is the following, based on total assembly fuel mass:

$$522.0 \ \frac{kg}{assy} \times \frac{1000 \ g}{kg} \times \frac{assy}{264 \ rods} \times \frac{rod}{\pi \times (0.3225/2 \ in)^2 \times 144 \ in} \times \frac{in^3}{2.54^3 \ cm^3} = \mathbf{10.257 \ g/cc}$$

3. OPERATING CONDITIONS

Table 18 provides assumptions and references for pertinent core conditions and properties for WBN1 Cycle 1.

Table 18: Core Operating Conditions

Description	Value	Reference
Coolant inlet temperature	565 K	2 (557.7 °F)
Coolant core average temperature at HFP	585 K	2 (592.8 °F)
Reactor system pressure	2250 psi	2
Rated Core Power	3411 MW	1
Rated Coolant total flow rate	144.7 Mlbs/hr	1
Coolant Core bypass flow fraction	9%	1
Average fraction of heat generated in the fuel	97.4%	1
RCCA Control Bank Overlap	128 steps	2
Cycle 1 Length	441.0 EFPDs	17
Cycle 1 EOC Exposure	16.939 GWd/MT	17
Cycle 1 HZP BOC ARO critical soluble boron concentration	1291 ppm	16
Cycle 1 Uranium Fuel Loading	88.808 MT	1

- The core bypass flow fraction is approximate. The actual listed design value is <9%.
- The Cycle 1 length and EOC exposure is calculated based on measured data from WBN1 and the operating history leading up to the Cycle 2 refueling outage, correcting for slight differences in the core fuel loading.
- The boron concentration is based on a measured value of 1299 ppm assuming 19.78 at%. The value provided is the equivalent at 19.9 at%. For the majority of calculations in this specification, **1300 ppm** is used for simplicity.
- The core loading is calculated based on data in Reference 1 as:

$$193 \ assys \times 522.0 \ \frac{kg}{assy} \times 0.8815 \frac{kgU}{kgUO_2} = \mathbf{88.808 \ MT}$$

4. CORE PHYSICS PROBLEMS

Problem #1: 2D HZP BOC Pin Cell

PURPOSE

The first VERA core physics benchmark problem demonstrates VERA's capability to solve a simple two-dimensional pin cell eigenvalue problem typical of PWR reactor analyses, as shown in Figure P1-1.
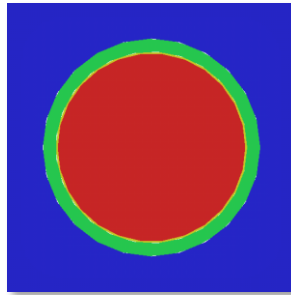
Figure P1-1: Problem 1 KENO-VI Geometry

SPECIFICATIONS

The problem consists of a single Westinghouse 17x17-type fuel rod cell at beginning-of-life (BOL) conditions based on the specification provided in Section 1.1. The materials are standard for this type of reactor: UO_2, Zircaloy-4, and water. The moderator also contains soluble boron as a chemical shim for maintaining criticality. The pellet-clad gap consists of helium gas, but this material may be neglected due to its insignificant neutron cross section.

This problem will be divided into five calculations. The first (part A) represents typical zero power isothermal conditions which are representative of power reactor startup physics testing. Calculations B, C, and D are for the same rod geometry but with a range of fuel temperatures that are common under full power operating conditions. Problem 1E is an IFBA fuel rod per section 1.9. Input specifications are provided below.

Table P1-1: Problem 1 Calculations

Problem	Moderator Temperature†	Fuel Temperature	Moderator Density
1A	565 K	565 K	0.743 g/cc
1B	600 K	600 K	0.661 g/cc
1C	↓	900 K	↓
1D	↓	1200 K	↓
1E	↓	600 K	0.743 g/cc

†Clad temperature set at moderator temperature

Table P1-2: Problem 1 Input Specification

Input	Value	Section
Fuel Density	10.257 g/cc	2.2
Fuel Enrichment	3.1%	2.1
Power	0% FP	--
Reactor Pressure	2250 psia	3.
Boron Concentration	1300 ppm	3.

- The fuel enrichment is the maximum of the three regions of Watts Bar Nuclear 1 Cycle 1 (WBN1C1) (Ref. 2).
- The fuel temperatures are assumed to approximately span the typical range under operating conditions. The temperature is assumed to be uniform across the pellet.
- The moderator densities correspond to the input temperature and core pressure conditions (Ref. 4), except for case 1E.

MATERIAL PROPERTIES

All material properties are listed in Section 2.

CAPABILITIES

Successful completion of this benchmark problem can be used to demonstrate the following capabilities:

- Input based on reactor geometry, fuel enrichment, boron concentration, etc.
- Calculate atomic number densities of each material composition
- Automatically obtain fine-group microscopic cross sections for each mixture/material
- Perform resonance self-shielding calculation for each unique fuel pin and material
- Perform cross section energy collapse based on local flux spectrum
- Create transport mesh
- Perform properly weighted cross section homogenization for each mixed transport cell
- Build and execute core simulator on target computer platform
- Output eigenvalue
- Validate eigenvalue against CE Monte Carlo calculations

REFERENCE SOLUTION

The reference values for this benchmark problem are calculated by the SCALE 6.2 Beta (Ref. 6) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The CSAS6 sequence for KENO-VI uses input that includes materials, densities, fuel isotopics, an exact geometry description, and other code options. For this small problem, KENO-VI can provide an approximate solution within a small range of uncertainty using the precise geometry specification. CE cross section libraries are available for both 565K and 600K. This calculation is documented below.

Cross Sections

The reference solution is based on ENDF/B-VII.0 CE cross sections as obtained from SCALE 6.2 (**ce-v7-endf**) (Ref. 6). Both 565K and 600K cross sections are utilized. For the isotope H-1, the S(α,β) scattering data is not interpolated internally and is only available at 550K and 600K. Therefore, for the 565K cases a secondary calculation was performed and the final result was manually interpolated.

Materials

The SCALE 6 material processor MIPLIB allows common input of compositions across most SCALE codes and sequences. For this problem, the materials are input nearly exactly as described in this specification, with the following exceptions:

- The fuel isotopes are calculated based on the equations in Table 17 (and Ref. 5) and are provided here.

Table P1-3: Problem 1 Calculated Fuel Isotopic Input

Isotope	Weight Percent
U-234	0.0263%
U-235	3.1%
U-236	0.0143%
U-238	96.8594%

*Note that explicit O-16 is not needed in MIPLIB input

- For the reference calculation, the pellet-clad gap is modeled explicitly as Helium with nominal density. This could also be modeled as 'void' or air.
- The boron concentration is input by use of weight fractions with the H_2O and boron MIPLIB compositions. For 1300 ppm, the corresponding weight fraction is 0.0013, and the water fraction is 0.9987.

Parameters

Because this is a reference calculation and the geometry is reasonably small, the number of particle histories is 1.1e8, utilizing 1100 generations with 100,000 particles per generation, skipping 100 generations. This limits the standard deviation in the resulting k-effective to approximately 8 pcm (actual uncertainties will be provided in the results).

Geometry

The pin cell geometry will be modeled explicitly with concentric fuel, gap, and cladding cylinders using the radii provided in Table 1. The IFBA pin is modeled based on data in Table 11. Reflective boundary conditions are applied on all sides. Figure P1-1 shows the exact KENO geometry used.

Input Files

A sample CE KENO-VI input file for problem 1A is included in Appendix A. The inputs for all files are currently located on cpile2.ornl.gov in location **/home/agm/vera**.

Computer Code

The reference calculations were executed with SCALE 6.2 Beta 2 on the Fission supercomputer at Idaho National Laboratory. The approximate run time was 22 minutes on 192 cores, utilizing less than 2 GB of memory per core.

Mixing Table

The following table provides the precise isotopic number densities used for each mixture in the reference problems.

Table P1-4: Reference Mixing Table

Material	Isotope ID	Atom Density (/barn-cm)
Fuel (3.1%)	92234	6.11864E-06
	92235	7.18132E-04
	92236	3.29861E-06
	92238	2.21546E-02
	8016	4.57642E-02
Gap	2004	2.68714E-05
Cladding (Zirc-4)	40090	2.18865E-02
	40091	4.77292E-03
	40092	7.29551E-03
	40094	7.39335E-03
	40096	1.19110E-03
	50112	4.68066E-06
	50114	3.18478E-06
	50115	1.64064E-06
	50116	7.01616E-05
	50117	3.70592E-05
	50118	1.16872E-04
	50119	4.14504E-05
	50120	1.57212E-04
	50122	2.23417E-05
	50124	2.79392E-05
	26054	8.68307E-06
	26056	1.36306E-04
	26057	3.14789E-06
	26058	4.18926E-07
	24050	3.30121E-06
	24052	6.36606E-05
	24053	7.21860E-06
	24054	1.79686E-06
	72174	3.54138E-09
	72176	1.16423E-07
	72177	4.11686E-07
	72178	6.03806E-07
	72179	3.01460E-07
	72180	7.76449E-07
Moderator (1A,1E)	8016	2.48112E-02
	1001	4.96224E-02
	5010	1.07070E-05
	5011	4.30971E-05
Moderator (1B-1D)	8016	2.20729E-02
	1001	4.41459E-02
	5010	9.52537E-06
	5011	3.83408E-05
IFBA (1E)	5010	2.16410E-02
	5011	1.96824E-02
	40090	1.06304E-02
	40091	2.31824E-03
	40092	3.54348E-03
	40094	3.59100E-03
	40096	5.78528E-04

REFERENCE SOLUTION RESULTS

The following table contains the results from the CE KENO-VI calculations for Problem 1. Reference results and isotopics for the same cases using ENDF/B-VI.8 cross sections are included in Appendix A.

Table P1-5: Problem 1 Reference Solution Results

Problem	Integral Absorber	Moderator Temperature	Fuel Temperature	Moderator Density	k-effective
1A	None	565 K	565 K	0.743 g/cc	**1.187038 ± 0.000054**
1B	None	600 K	600 K	0.661 g/cc	**1.182149 ± 0.000068**
1C	None	↓	900 K	↓	**1.171722 ± 0.000072**
1D	None	↓	1200K	↓	**1.162603 ± 0.000071**
1E	IFBA	↓	600 K	0.743 g/cc	**0.771691 ± 0.000076**

Problem #2: 2D HZP BOC Fuel Lattice

PURPOSE

The second VERA core physics benchmark problem demonstrates VERA's capabilities for modeling a simple two-dimensional array of fuel rods (a fuel lattice) typical of the central axial region of PWR fuel assemblies. In addition to the multiplication factor, the results also permit comparison of the normalized fission reaction rate distribution (herein referred to as 'pin powers') among the fuel rods.
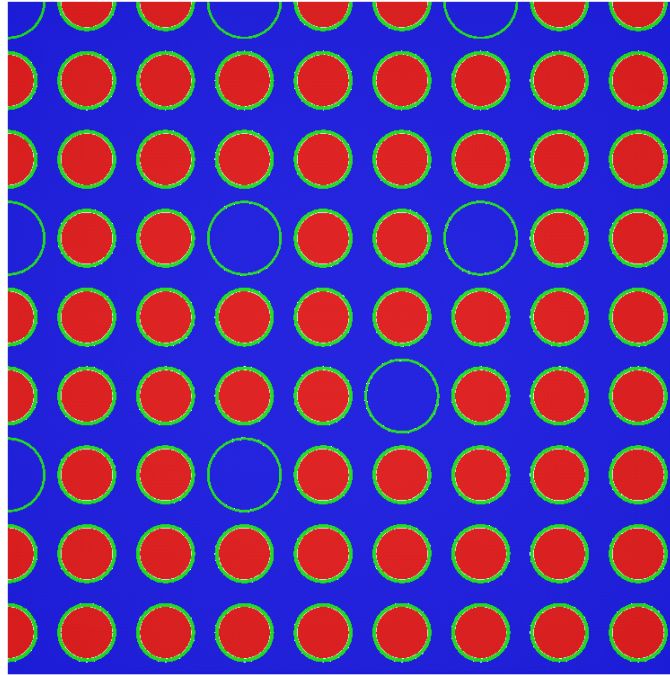
Figure P2-1: Problem 2 KENO-VI Geometry

SPECIFICATIONS

The problem consists of a single Westinghouse 17x17-type fuel lattice at beginning-of-life (BOL) as depicted in Figure 3. The parameters for the fuel itself are described in Sections 1.1 and 1.2. Other materials such as silver-indium-cadmium (AIC), boron carbide (B_4C), Pyrex (borosilicate glass - B_2O_3-SiO_2), and B_4C-Al_2O_3 are used for neutron poisons inserted into the guide tubes (Sections 1.5 1.6, and 1.10), and stainless steel 304 is used for the instrument tube thimble (Section 1.8) and other structural materials. Integral burnable absorbers such as IFBA and Gadolinia are also included in some of the test cases.

This problem will be divided into several calculations. The first (part A) represents typical zero power isothermal conditions which are representative of power reactor startup physics testing. Other calculations (parts B, C, and D) are for the same geometry but with a range of fuel temperatures that are common under full power operating conditions, consistent with problem 1. Parts 2E to 2P test the capability to accurately model radial heterogeneities created by different burnable poisons and control rod types. Finally, 2Q tests a code's capability to accurately model the reactivity depression and radial power distribution produced by a spacer grid with uniformly distributed mass. Input specifications are provided below in Tables P2-1, P2-2, and P2-3.

Table P2-1: Problem 2 Calculations

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	↓	↓	↓
2Q	Zircaloy Spacer Grid	565 K	565 K	↓

†Clad temperature set at moderator temperature

Table P2-2: Problem 2 Input Specification

General Input	Value	Section
Nominal Fuel Density	10.257 g/cc	2.2
Nominal Fuel Enrichment	3.1%	2.1
Power	0% FP	--
Reactor Pressure	2250 psia	3.
Boron Concentration	1300 ppm	3.
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	1.11

- The nominal fuel enrichment is the maximum of the three regions of Watts Bar Nuclear 1 Cycle 1 (WBN1C1) (Ref. 2).
- For problem 2K, the low enriched rods are the same enrichment as other problems. The rest are 0.5% higher. The arrangement of these rods is shown in the figure below.
- The rods containing gadolinia are assumed to be enriched only to 1.8% U-235. This value is estimated based on data contained in Reference 15.
- The fuel temperatures are assumed to approximately span the typical range under operating conditions.
- 600K is used for coolant and cladding temperatures rather than 565K to be consistent with available CE cross section libraries (at the time).
- For problems 2A-2D, the moderator densities correspond to the input temperature and core pressure conditions (Reference 4). For the other problems, the density corresponding to the average value at zero power is used for simplicity.
- The spacer grid data for 2Q are included in Table 3. The spacer sleeves are ignored.

The lattice layouts for the problems are provided in Figure P2-2 below.
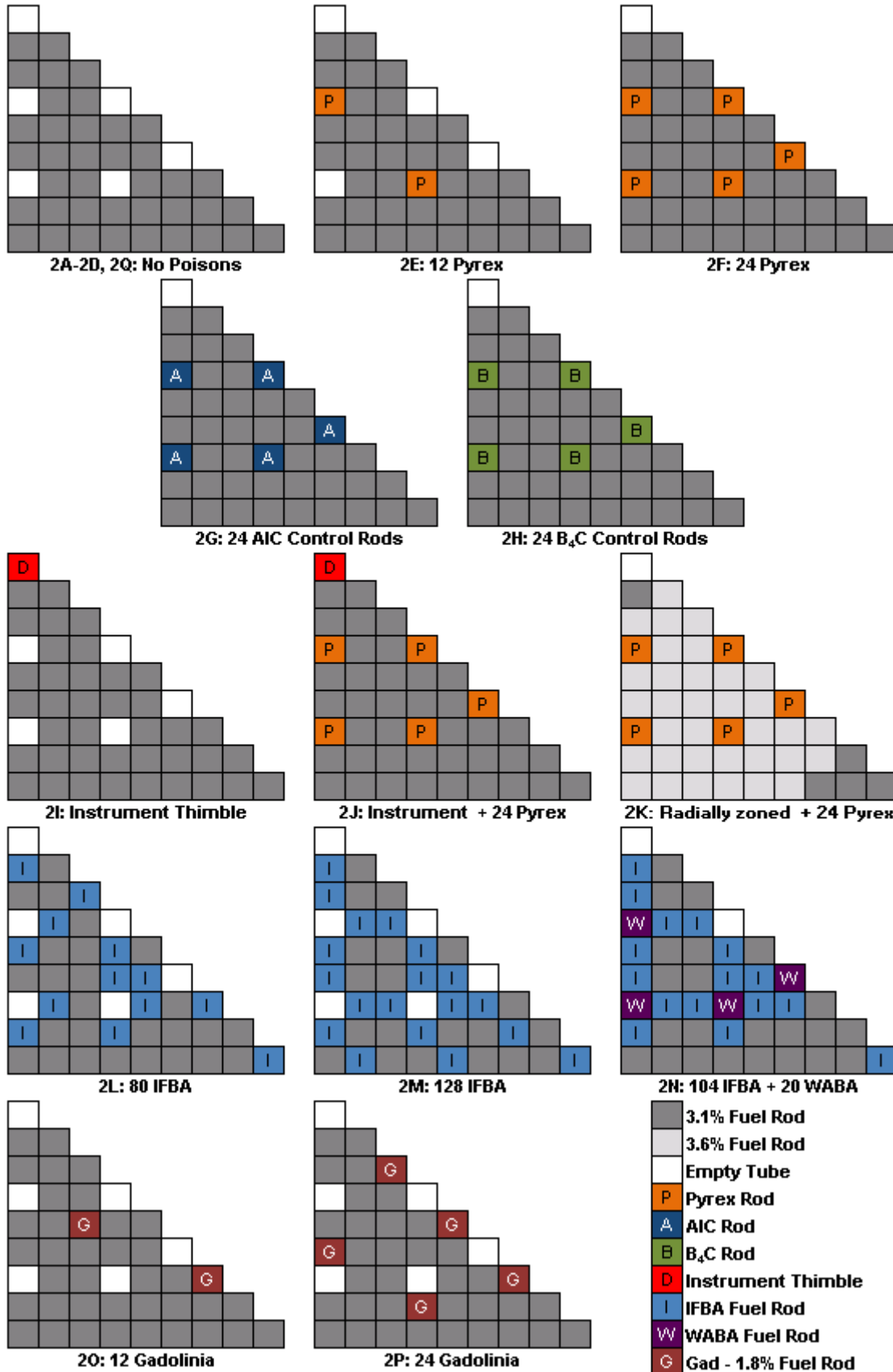
Figure P2-2: Problem 2 Lattice Layouts (Octant Symmetry)

MATERIAL PROPERTIES

All material properties are listed in Section 2.

CAPABILITIES

Successful completion of this benchmark problem can be used to demonstrate the following capabilities:

- Account for spatial effects on cross sections
- Account for spatial effects on energy collapse
- Provide parallelization for pin-by-pin cross section processing
- Account for assembly gap in transport mesh
- Permit reflective quarter or eighth symmetry
- Account for effects of prompt and delayed gammas on pin powers
- Properly treat thin absorbing pellet coatings such as IFBA
- Account for reactivity and power distribution effects from spacer grids
- Output pin-by-pin relative reaction rates / power
- Provide flux and power distribution visualization
- Validate pin powers against CE Monte Carlo calculations
- Compare performance to NRC licensed and/or established industry code(s)

REFERENCE SOLUTION

The reference values for this benchmark problem are calculated by the SCALE 6.2 Beta (Ref. 6) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The CSAS6 sequence for KENO-VI uses input that includes materials, densities, fuel isotopics, an exact geometry description, and other code options. For this problem, KENO-VI can provide an approximate eigenvalue solution within a small range of uncertainty using the precise geometry specification. It can also perform fission rate tallies for each fuel rod, which are normalized and post-processed to produce the pin power distribution as well as a distribution of uncertainties.

Cross Sections

The reference solution is based on ENDF/B-VII.0 CE cross sections as obtained from SCALE 6.2 (**ce-v7-endf**) (Ref. 6). Both 565K and 600K cross sections are utilized. For the isotope H-1, the $S(\alpha,\beta)$ scattering data is not interpolated internally and is only available at 550K and 600K. Therefore, for the 565K cases a secondary calculation was performed and the final result was manually interpolated.

Materials

The SCALE 6 material processor MIPLIB allows common input of compositions across most SCALE codes and sequences. For this problem, the materials are input nearly exactly as described in this specification, with the following exceptions:

- The fuel isotopes are calculated based on the equations in Table 17 (and Ref. 5) and are provided here.

Table P2-3: Problem 2 Calculated Fuel Isotopic Input vs. Enrichment

Isotope	1.8%	3.1%	3.6%
U-234	0.0146%	0.0263%	0.0310%
U-235	1.8%	3.1%	3.6%
U-236	0.0083%	0.0143%	0.0166%
U-238	98.1771%	96.8594%	96.3525%

*Note that explicit O-16 is not needed in MIPLIB input

- For the reference calculations, the pellet-clad gap is modeled explicitly as Helium with nominal density. This could also be modeled as 'void' or air. Other gaps in control and absorber rods are handled in the same manner.
- The boron concentration is input by use of weight fractions with the H$_2$O and boron MIPLIB compositions. For 1300 ppm, the corresponding weight fraction is 0.0013, and the water fraction is 0.9987.

Parameters

In order to get the power distribution uncertainty as low as possible an extremely large number of particles was used. In this case, 1.1e9 particles are used, using 1100 generations with 1e6 particles per generation, skipping 100 generations. This resulted in an eigenvalue uncertainty of less than **3 pcm** and a maximum power distribution uncertainty of less than **0.06%**.

Geometry

The pin cell geometry will be modeled explicitly with concentric fuel, gap, and cladding cylinders using the radii provided in Section 1. The lattice is modeled according to Section 1.2 in quarter symmetry, including the assembly gaps. Each of the burnable poisons and discrete inserts are modeled as described in Section 1. Reflective boundary conditions are applied on all sides. Figures P2-4 to P2-19 show the exact KENO-VI geometry for each of the problems.

Note that the spacer grid model used for case 2Q assumes that an equal mass of Zircaloy is contained in each lattice cell. Therefore, the grid mass in each cell is uniformly 1/289 of the total grid mass, and no grid material is placed in the inter-assembly gap. The lattice cell model is an explicit outer strap, where the grid mass for each cell is placed as an outer rectangular box. This can be observed in Figure P2-19.

Input Files

The CE KENO-VI input files for this problem are unreasonably large to be included in this document. They are located on cpile2.ornl.gov in location **/home/agm/vera**.

Computer Code

The reference calculations were executed with SCALE 6.2 Beta 2 on the Fission supercomputer at Idaho National Laboratory. The approximate run time was 3 hours on 300 cores, utilizing up to 2.7 GB of memory per core.

Mixing Table

The following table provides the precise isotopic number densities used for each mixture in the reference problems.

Table P2-4: Reference Mixing Table

Material	Isotope ID	Atom Density (/barn-cm)
3.1% Fuel	92234	6.11864E-06
	92235	7.18132E-04
	92236	3.29861E-06
	92238	2.21546E-02
	8016	4.57642E-02
Gap	2004	2.68714E-05
Cladding and Grid	24050	3.30121E-06
	24052	6.36606E-05
	24053	7.21860E-06
	24054	1.79686E-06
	26054	8.68307E-06
	26056	1.36306E-04
	26057	3.14789E-06
	26058	4.18926E-07
	40090	2.18865E-02
	40091	4.77292E-03
	40092	7.29551E-03
	40094	7.39335E-03
	40096	1.19110E-03
	50112	4.68066E-06
	50114	3.18478E-06
	50115	1.64064E-06
	50116	7.01616E-05
	50117	3.70592E-05
	50118	1.16872E-04
	50119	4.14504E-05
	50120	1.57212E-04
	50122	2.23417E-05
	50124	2.79392E-05
	72174	3.54138E-09
	72176	1.16423E-07
	72177	4.11686E-07
	72178	6.03806E-07
	72179	3.01460E-07
	72180	7.76449E-07
Moderator 0.743 g/cc (2A,2E-2P)	8016	2.48112E-02
	1001	4.96224E-02
	5010	1.07070E-05
	5011	4.30971E-05
Moderator 0.661 g/cc (2B-2D)	8016	2.20729E-02
	1001	4.41459E-02
	5010	9.52537E-06
	5011	3.83408E-05
Pyrex (2E,2F, 2J,2K)	5010	9.63266E-04
	5011	3.90172E-03
	8016	4.67761E-02
	14028	1.81980E-02
	14029	9.24474E-04
	14030	6.10133E-04
SS304 (2E-2K)	6000	3.20895E-04
	14028	1.58197E-03
	14029	8.03653E-05
	14030	5.30394E-05
	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
AIC (2G)	47107	2.36159E-02
	47109	2.19403E-02
	48106	3.41523E-05
	48108	2.43165E-05
	48110	3.41250E-04
	48111	3.49720E-04
	48112	6.59276E-04
	48113	3.33873E-04
	48114	7.84957E-04
	48116	2.04641E-04
	49113	3.44262E-04
	49115	7.68050E-03
B_4C (2H)	5010	1.52689E-02
	5011	6.14591E-02
	6000	1.91820E-02
3.6% Fuel (2K)	92234	7.21203E-06
	92235	8.33952E-04
	92236	3.82913E-06
	92238	2.20384E-02
	8016	4.57669E-02
IFBA ZrB_2 (2L-2N)	5010	2.16410E-02
	5011	1.96824E-02
	40090	1.06304E-02
	40091	2.31824E-03
	40092	3.54348E-03
	40094	3.59100E-03
	40096	5.78528E-04
WABA B_4C-Al_2O_3 (2N)	5010	2.98553E-03
	5011	1.21192E-02
	6000	3.77001E-03
	8016	5.85563E-02
	13027	3.90223E-02
Gadolinia 5% Gd_2O_3 95% UO_2 1.8% Fuel (2O,2P)	92234	3.18096E-06
	92235	3.90500E-04
	92236	1.79300E-06
	92238	2.10299E-02
	64152	3.35960E-06
	64154	3.66190E-05
	64155	2.48606E-04
	64156	3.43849E-04
	64157	2.62884E-04
	64158	4.17255E-04
	64160	3.67198E-04
	8016	4.53705E-02

REFERENCE SOLUTION RESULTS

The following table contains the results from the CE KENO-VI reference calculations. The subsequent figures display the calculated normalized fission rate distributions and associated reaction rate uncertainties. These calculations were also repeated with ENDF/B-VI.8 CE cross sections, and these results are provided in Appendix C (except for Problem 2Q).

Also, note that the reference KENO-VI results are calculated in quarter assembly geometry, but are collapsed to one eighth assembly results. The symmetric fuel rod powers are averaged, and the symmetric sigmas are averaged and divided by the square root of two, as the estimate of the uncertainty is inversely proportional to the square root of the population size.

Table P2-5: Problem 2 Reference Solution Eigenvalue Results

Problem	Description	Fuel Temperature	Moderator Density	k-effective
2A	No Poisons	565 K	0.743 g/cc	1.182175 ± 0.000017
2B	↓	600 K	0.661 g/cc	1.183360 ± 0.000024
2C	↓	900 K	↓	1.173751 ± 0.000023
2D	↓	1200 K	↓	1.165591 ± 0.000023
2E	12 Pyrex	600 K	0.743 g/cc	1.069627 ± 0.000024
2F	24 Pyrex	↓	↓	0.976018 ± 0.000026
2G	24 AIC	↓	↓	0.847695 ± 0.000025
2H	24 B4C	↓	↓	0.788221 ± 0.000025
2I	Instrument Thimble	↓	↓	1.179916 ± 0.000024
2J	Instrument + 24 Pyrex	↓	↓	0.975193 ± 0.000025
2K	Zoned + 24 Pyrex	↓	↓	1.020063 ± 0.000025
2L	80 IFBA	↓	↓	1.018915 ± 0.000024
2M	128 IFBA	↓	↓	0.938796 ± 0.000025
2N	104 IFBA + 20 WABA	↓	↓	0.869615 ± 0.000025
2O	12 Gadolinia	↓	↓	1.047729 ± 0.000024
2P	24 Gadolinia	↓	↓	0.927410 ± 0.000024
2Q	Zircaloy Spacer Grid	565 K	↓	1.171940 ± 0.000016
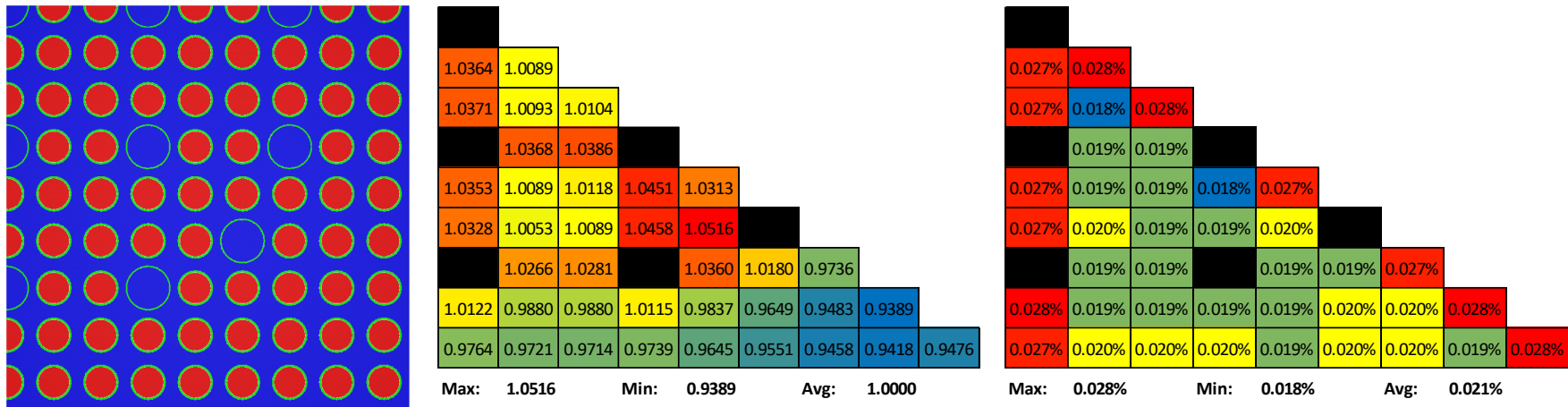
Figure P2-3: Problem 2A (565K) CE KENO-VI Power Distribution Results
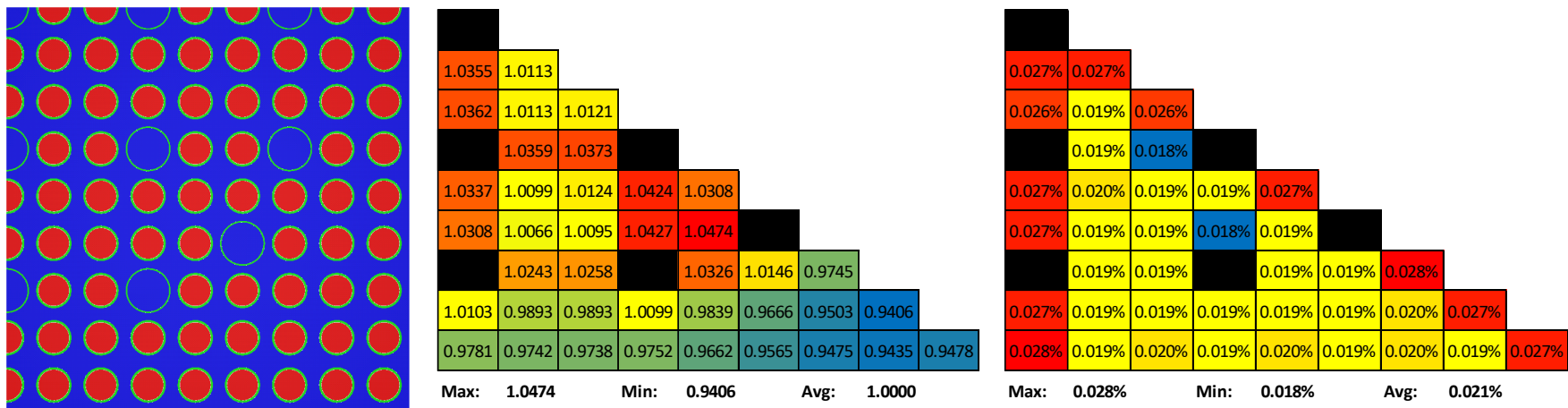
Figure P2-4: Problem 2B (600K) CE KENO-VI Power Distribution Results
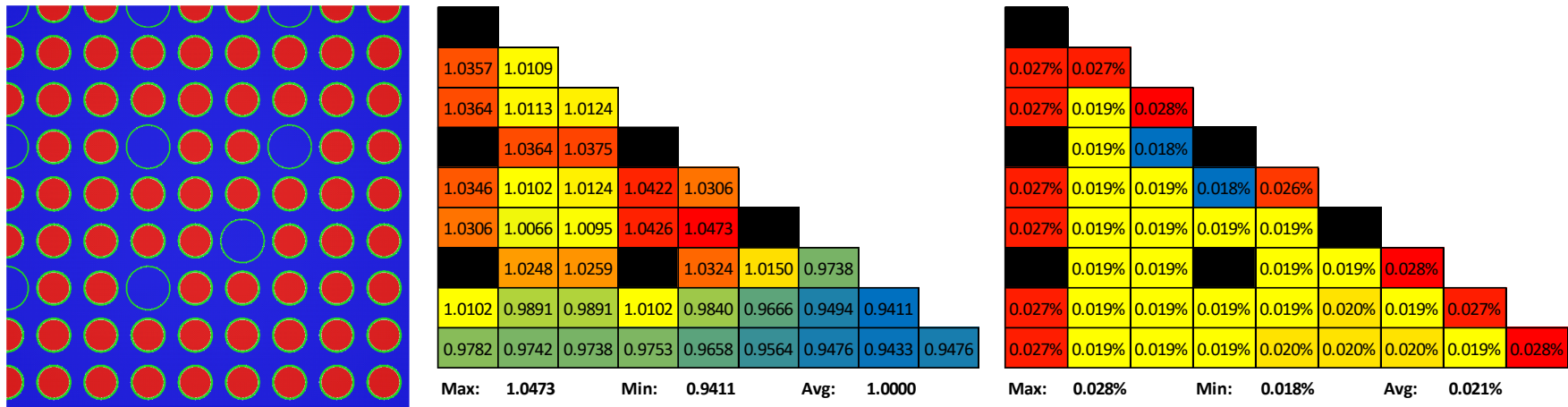
Figure P2-5: Problem 2C (900K) CE KENO-VI Power Distribution Results

Figure P2-6: Problem 2D (1200K) CE KENO-VI Power Distribution Results

1.0170	0.9930						
0.9299	0.9635	0.9962					
	0.9331	1.0250					
0.9347	0.9695	1.0022	1.0362	1.0290			
1.0290	1.0034	0.9751	0.9523	1.0226			
	1.0350	0.9419		0.9579	1.0426	1.0314	
1.0578	1.0222	0.9763	0.9355	0.9787	1.0146	1.0246	1.0290
1.0346	1.0238	1.0054	0.9938	1.0054	1.0218	1.0314	1.0398	1.0514

Max: 1.0578   Min: 0.9299   Avg: 1.0000

0.029%	0.029%						
0.029%	0.021%	0.027%					
	0.021%	0.020%					
0.029%	0.020%	0.020%	0.019%	0.027%			
0.029%	0.020%	0.020%	0.021%	0.020%			
	0.020%	0.020%		0.021%	0.019%	0.028%	
0.028%	0.020%	0.020%	0.021%	0.020%	0.019%	0.020%	0.028%
0.028%	0.020%	0.021%	0.020%	0.020%	0.020%	0.020%	0.020%	0.028%

Max: 0.029%   Min: 0.019%   Avg: 0.022%

Figure P2-7: Problem 2E (12 Pyrex) CE KENO-VI Power Distribution Results

1.0783	1.0428						
0.9714	0.9907	0.9736					
	0.9333	0.9262					
0.9258	0.9591	0.9543	0.9118	0.9262			
0.9280	0.9617	0.9587	0.9127	0.9070			
	0.9420	0.9411		0.9350	0.9670	1.0340	
0.9744	1.0047	1.0060	0.9793	1.0191	1.0502	1.0831	1.1094
1.0472	1.0529	1.0551	1.0551	1.0717	1.0923	1.1138	1.1339	1.1541

Max: 1.1541   Min: 0.9070   Avg: 1.0000

0.029%	0.029%						
0.030%	0.022%	0.030%					
	0.022%	0.022%					
0.031%	0.022%	0.022%	0.022%	0.030%			
0.030%	0.021%	0.022%	0.022%	0.022%			
	0.023%	0.022%		0.021%	0.022%	0.029%	
0.030%	0.021%	0.022%	0.021%	0.021%	0.020%	0.020%	0.029%
0.029%	0.021%	0.021%	0.021%	0.021%	0.021%	0.021%	0.019%	0.028%

Max: 0.031%   Min: 0.019%   Avg: 0.023%

Figure P2-8: Problem 2F (24 Pyrex) CE KENO-VI Power Distribution Results

1.0732	1.0353							
0.9393	0.9660	0.9411						
	0.8855	0.8762						
0.8736	0.9200	0.9138	0.8529	0.8719				
0.8784	0.9273	0.9212	0.8559	0.8507				
	0.9083	0.9072		0.9070	0.9646	1.0707		
0.9646	1.0058	1.0098	0.9778	1.0394	1.0944	1.1525	1.1999	
1.0707	1.0803	1.0858	1.0899	1.1202	1.1585	1.2005	1.2363	1.2666

Max: 1.2666   Min: 0.8507   Avg: 1.0000

0.030%	0.031%							
0.033%	0.022%	0.032%						
	0.024%	0.024%						
0.034%	0.023%	0.023%	0.024%	0.034%				
0.034%	0.023%	0.023%	0.024%	0.024%				
	0.023%	0.023%		0.023%	0.023%	0.030%		
0.032%	0.022%	0.023%	0.022%	0.022%	0.021%	0.021%	0.028%	
0.031%	0.022%	0.022%	0.022%	0.021%	0.021%	0.021%	0.020%	0.029%

Max: 0.034%   Min: 0.020%   Avg: 0.024%

Figure P2-9: Problem 2G (AIC) CE KENO-VI Power Distribution Results

1.0607	1.0215							
0.9221	0.9481	0.9210						
	0.8646	0.8547						
0.8516	0.9001	0.8931	0.8311	0.8511				
0.8589	0.9093	0.9032	0.8361	0.8344				
	0.8952	0.8962		0.9022	0.9707	1.0905		
0.9609	1.0041	1.0104	0.9802	1.0495	1.1144	1.1840	1.2416	
1.0751	1.0862	1.0943	1.1019	1.1405	1.1873	1.2384	1.2829	1.3188

Max: 1.3188   Min: 0.8311   Avg: 1.0000

0.033%	0.032%							
0.034%	0.024%	0.034%						
	0.025%	0.025%						
0.036%	0.024%	0.025%	0.025%	0.036%				
0.035%	0.025%	0.024%	0.025%	0.025%				
	0.025%	0.025%		0.024%	0.024%	0.032%		
0.033%	0.023%	0.023%	0.023%	0.022%	0.022%	0.021%	0.030%	
0.032%	0.022%	0.022%	0.022%	0.022%	0.022%	0.021%	0.021%	0.029%

Max: 0.036%   Min: 0.021%   Avg: 0.025%

Figure P2-10: Problem 2H (B₄C) CE KENO-VI Power Distribution Results

Figure P2-11: Problem 2I (Instrument Thimble) CE KENO-VI Power Distribution Results
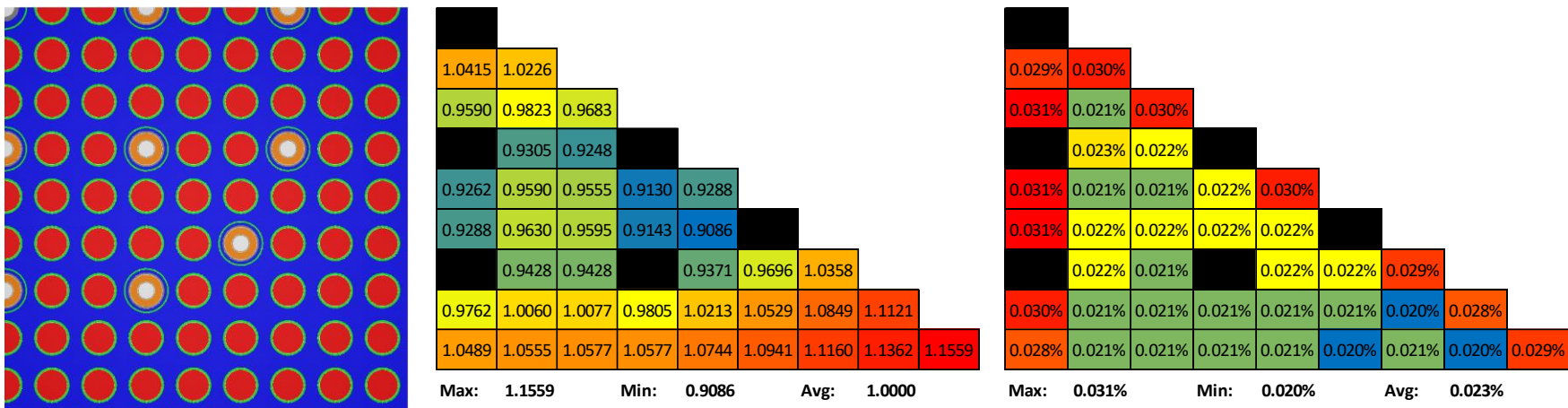
Figure P2-12: Problem 2J (Instrument and Pyrex) CE KENO-VI Power Distribution Results
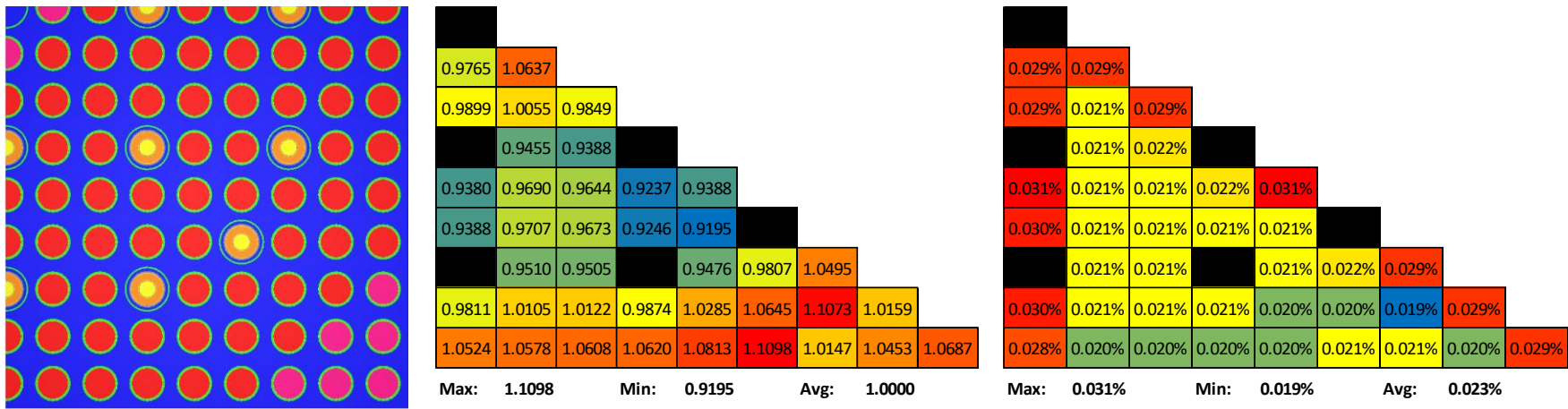
Figure P2-13: Problem 2K (Zoned and 24 Pyrex) CE KENO-VI Power Distribution Results
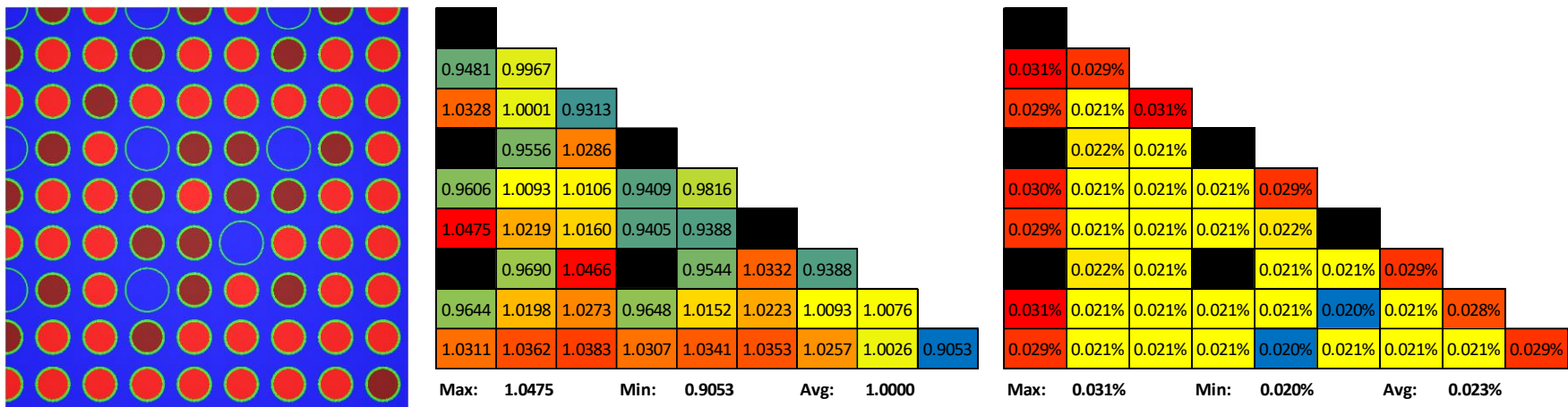
Figure P2-14: Problem 2L (80 IFBA) CE KENO-VI Power Distribution Results

0.9833	1.0389						
0.9846	1.0393	1.0389					
	0.9833	0.9824					
0.9828	1.0370	1.0361	0.9760	1.0206			
0.9814	1.0361	1.0343	0.9714	0.9696			
	0.9769	0.9778		0.9696	0.9659	1.0042	
0.9728	1.0193	1.0297	0.9792	1.0170	1.0170	0.9441	1.0152
1.0079	0.9432	1.0334	1.0288	0.9473	1.0325	1.0361	1.0306	0.9423

Max: 1.0393   Min: 0.9423   Avg: 1.0000

0.032%	0.030%						
0.031%	0.022%	0.030%					
	0.022%	0.022%					
0.031%	0.021%	0.021%	0.021%	0.030%			
0.031%	0.022%	0.021%	0.022%	0.022%			
	0.022%	0.023%		0.021%	0.022%	0.030%	
0.032%	0.022%	0.022%	0.022%	0.022%	0.022%	0.022%	0.031%
0.030%	0.022%	0.021%	0.021%	0.022%	0.022%	0.021%	0.021%	0.032%

Max: 0.032%   Min: 0.021%   Avg: 0.024%

Figure P2-15: Problem 2M (128 IFBA) CE KENO-VI Power Distribution Results

0.9756	1.0258						
0.8993	0.9963	1.0209					
	0.8923	0.9657					
0.8697	0.9722	1.0057	0.9468	0.9557			
0.8678	0.9644	0.9700	0.8651	0.8467			
	0.8819	0.8831		0.8705	0.9111	1.0554	
0.9247	1.0155	1.0180	0.9318	1.0367	1.0824	1.1272	1.1538
1.0800	1.0928	1.0962	1.0923	1.1184	1.1459	1.1661	1.1602	1.0603

Max: 1.1661   Min: 0.8467   Avg: 1.0000

0.032%	0.032%						
0.034%	0.022%	0.032%					
	0.024%	0.023%					
0.034%	0.023%	0.023%	0.023%	0.034%			
0.034%	0.023%	0.023%	0.023%	0.024%			
	0.024%	0.023%		0.023%	0.023%	0.031%	
0.033%	0.023%	0.022%	0.023%	0.022%	0.022%	0.021%	0.029%
0.031%	0.022%	0.022%	0.021%	0.022%	0.021%	0.021%	0.022%	0.031%

Max: 0.034%   Min: 0.021%   Avg: 0.025%

Figure P2-16: Problem 2N (104 IFBA + 20 WABA) CE KENO-VI Power Distribution Results
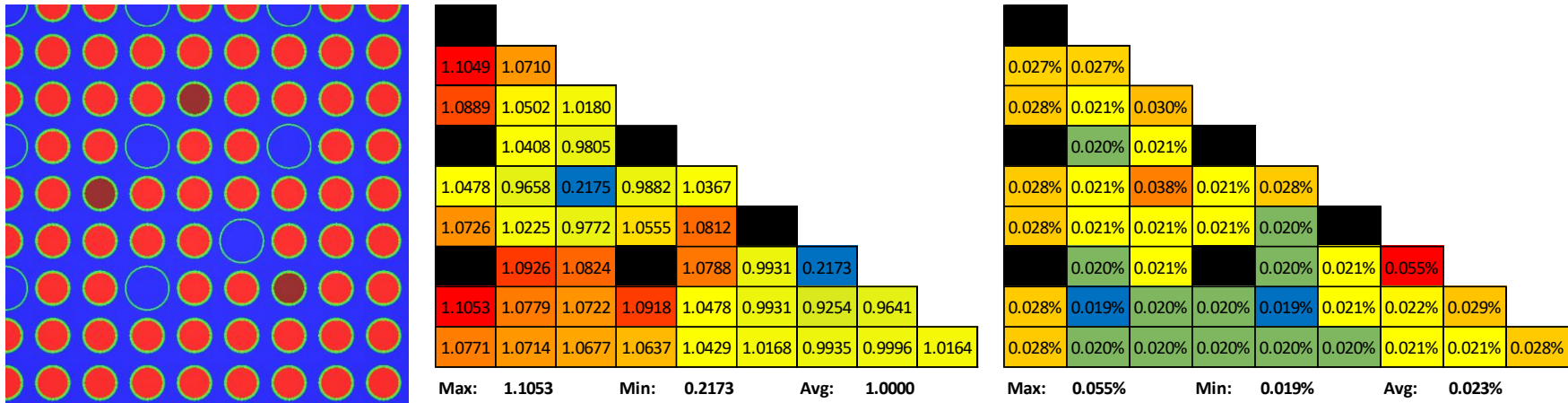
Figure P2-17: Problem 2O (12 Gadolinia) CE KENO-VI Power Distribution Results
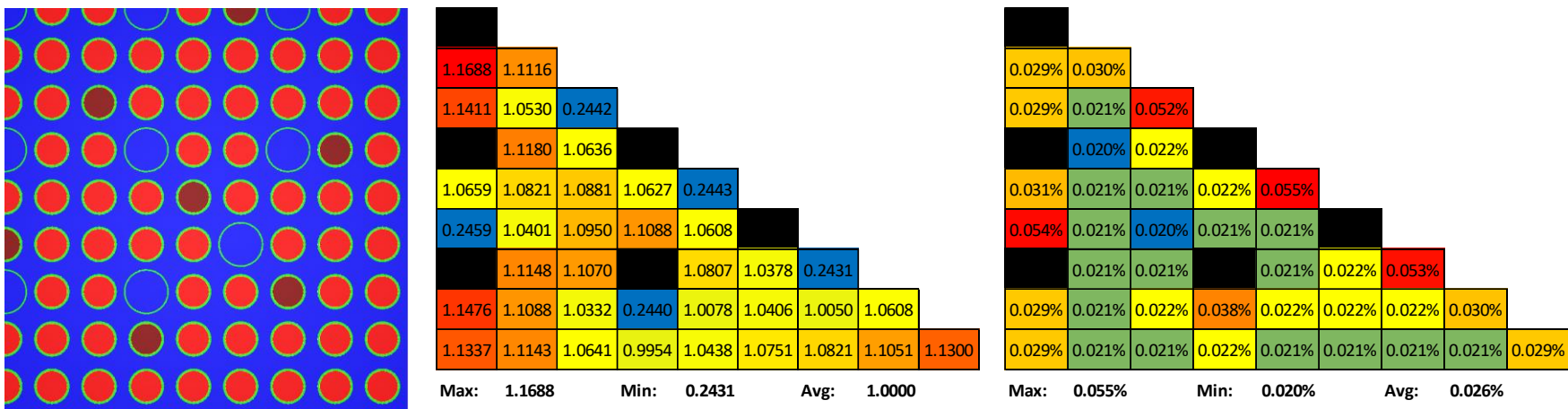
Figure P2-18: Problem 2P (24 Gadolinia) CE KENO-VI Power Distribution Results

1.0368	1.0105						
1.0371	1.0113	1.0120					
	1.0375	1.0389					
1.0353	1.0098	1.0124	1.0448	1.0331			
1.0320	1.0069	1.0098	1.0448	1.0513			
	1.0258	1.0273		1.0357	1.0160	0.9726	
1.0113	0.9883	0.9879	1.0109	0.9828	0.9639	0.9468	0.9369
0.9774	0.9726	0.9723	0.9745	0.9646	0.9548	0.9457	0.9413	0.9479

Max: 1.0513   Min: 0.9369   Avg: 1.0000

0.026%	0.027%						
0.027%	0.019%	0.026%					
	0.019%	0.019%					
0.027%	0.019%	0.019%	0.019%	0.027%			
0.027%	0.019%	0.019%	0.019%	0.018%			
	0.019%	0.019%		0.019%	0.019%	0.027%	
0.027%	0.020%	0.019%	0.018%	0.019%	0.019%	0.019%	0.027%
0.027%	0.019%	0.019%	0.019%	0.019%	0.020%	0.019%	0.020%	0.027%

Max: 0.027%   Min: 0.018%   Avg: 0.021%

Figure P2-19: Problem 2Q (Zircaloy Spacer Grid) CE KENO-VI Power Distribution Results

Problem #3: 3D HZP Assembly

PURPOSE

This core physics benchmark problem demonstrates VERA's performance for a simple three-dimensional fuel assembly typical of PWR reactor analyses. Successful completion demonstrates the capability to predict the eigenvalue and pin power distribution without thermal-hydraulic feedback or depletion.

SPECIFICATIONS

The problem consists of a single Westinghouse 17x17-type fuel assembly at beginning-of-life (BOL) and Hot Zero Power (HZP) isothermal conditions, based on the WBN1 data provided in Sections 1.1 to 1.4. The materials are standard for this type of reactor: UO_2 fuel, Zircaloy-4 cladding, Inconel-718, Stainless Steel Type 304, and water. The moderator also contains soluble boron as a chemical shim for maintaining criticality. The focus of this problem is to demonstrate resolution of spacer grid effects on the neutron flux, and to begin modeling the non-fuel structural materials above and below the fuel stack with corresponding boundary conditions.

The assembly problem represents the first three dimensional problem in the progression of capability and requires definition of axial neutron reflector regions in conjunction with non-reentrant boundaries (vacuum). Radially, the assembly can be treated in quarter symmetry with reflection as was done for Problem 2.

The problem is divided into two calculations. The differences in these calculations are described in Table P3-1 below.

Table P3-1: Problem 3 Input Specification

Input	3A	3B	Section
Fuel Density	10.257 g/cc	10.257 g/cc	2.2
Fuel Enrichment	3.1%	2.619%	2.1
Power	0% FP	0% FP	--
Inlet Coolant Temperature	600 K	565 K	--
Inlet Coolant Density	0.743 g/cc	0.743 g/cc	2.0
Reactor Pressure	2250 psia	2250 psia	3.
Boron Concentration	1300 ppm	1066 ppm	3.
Pyrex Burnable Poison Pattern	None	16	1.5

- The fuel enrichments are two of the three regions of Watts Bar Nuclear 1 Cycle 1 (WBN1C1) (Ref. 2).
- The fuel density is chosen to account for dishes and chamfers in the pellet stack, as described in Section 2.2
- The moderator density corresponds to 565K at the core pressure. (Reference 4).
- For 3A, 600K is used for coolant and cladding temperatures to be consistent with available CE cross section libraries (at the time). 565K (3B) is consistent with actual startup conditions.
- For 3B, the boron concentration of 1066 was chosen to make this problem close to critical (eigenvalue = 1.0).
- Problem 3B includes thimble plugs in the guide tubes which do not contain Pyrex rods. Problem 3A does not contain any thimble plugs.
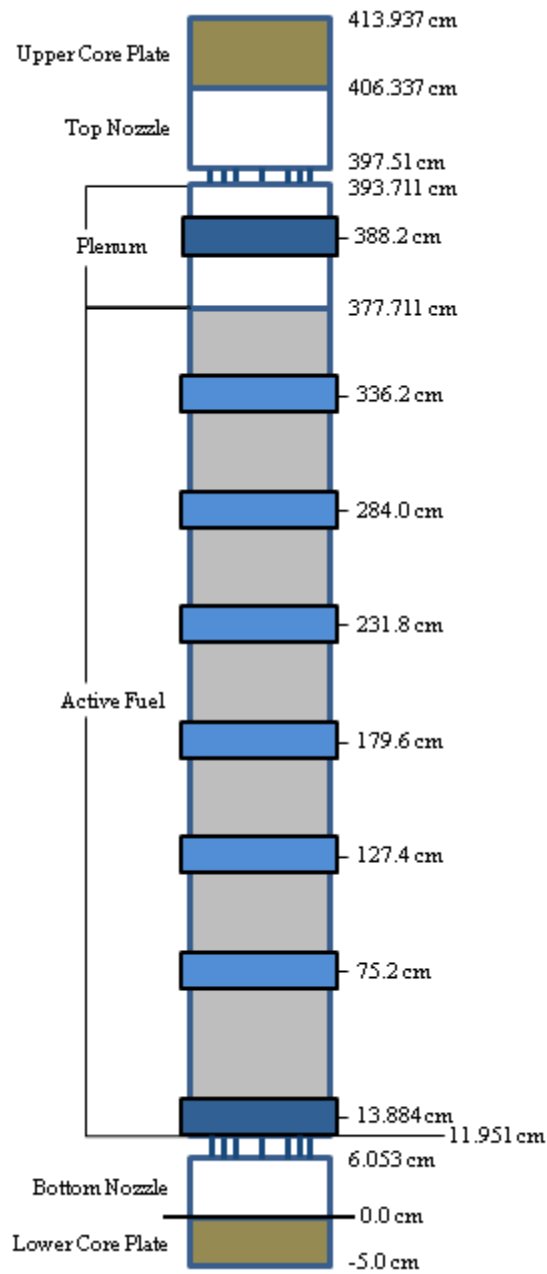
Figure P3-1: Problem 3 Axial Geometry (without end plugs)

MATERIAL PROPERTIES

All material properties are listed in Section 2.

CAPABILITIES

Successful completion of this benchmark problem can be used to demonstrate the following capabilities:

- Support multiple axial fuel regions
- Support explicit (plenum) and homogenized (nozzle) axial reflectors with vacuum boundary
- Perform axial placement and material homogenization for multiple spacer grid types

- Account for spacer grids on cross section processing
- Implement early automatic axial meshing strategy
- Demonstrate performance on HPC computing resources
- Output assembly level power distribution edits (1D, 2D, 3D power, axial offset)
- Provide concise and manageable method of relative pin power output
- Output peak relative pin power statistics (FdH, Fq) and locations

REFERENCE SOLUTION

The reference values for this benchmark problem are calculated by the SCALE 6.2 Beta (Ref. 6) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The CSAS6 sequence for KENO-VI uses input that includes materials, densities, fuel isotopics, an exact geometry description, and other code options. For this problem, KENO-VI can provide an approximate eigenvalue solution within a small range of uncertainty using the precise geometry specification. It can also perform fission rate tallies for each fuel rod at each prescribed axial location, which has been normalized and post-processed to produce the fission rate distribution as well as a distribution of uncertainties. This solution is only available at certain temperatures so 600K and 565K were used for these cases. This calculation is documented below.

Due to problem size and detail, including semi-explicit spacer grids and the need for unique units for each power region, a FORTRAN computer code was created to create the input automatically based on a series of simple problem descriptors. This input is too large to include in this document. This code is located at **/home/agm/git/kenogen**.

Cross Sections

The reference solution is based on ENDF/B-VII.0 CE cross sections as obtained from SCALE 6.2 (**ce-v7-endf**) (Ref. 6). Both 565K and 600K cross sections are utilized. For the isotope H-1, the $S(\alpha,\beta)$ scattering data is not interpolated internally and is only available at 550K and 600K. Therefore, for the 565K case a secondary calculation was performed and the final result was manually interpolated.

Materials

The SCALE 6.2 material processor MIPLIB allows common input of compositions across most SCALE codes and sequences. For this problem, the materials are input nearly exactly as described in this specification, with the following exceptions:

- The fuel isotopes are calculated based on the equations in Table 17 (and Ref. 5) and are provided here.

Table P3-2: Problem 3 Calculated Isotopic Input

Isotope	3A Wt%	3B Wt%
U-234	0.0263%	0.0219%
U-235	3.10%	2.619%
U-236	0.0143%	0.0120%
U-238	96.8594%	97.3471%

*Note that explicit O-16 is not needed in MIPLIB input

- For the reference calculation, the pellet-clad gap is modeled explicitly as Helium with nominal density. This could also be modeled as 'void' or air.

- The boron concentration is input by use of weight fractions with the H_2O and boron MIPLIB compositions. For 1300 ppm, the corresponding weight fraction is 0.0013, and the water fraction is 0.9987. For 1066 ppm, the input weight fraction is 0.001066.
- The material content for the top and bottom nozzles and top and bottom core plates was homogenized manually based on the material densities and heights. These materials are provided in the mixing table below. See Section 1.4 for a description of the axial reflector regions.

Parameters

A very large number of particle histories is needed to get the power distribution uncertainty low, especially in the regions of lowest power. In this case 25e9 particles, 5000 generations with 5e6 particles per generation, skipping 500 generations, produces less than **0.6 pcm** uncertainty in the eigenvalue and less than **0.16%** maximum uncertainty in pin power. The average pin power uncertainty for all locations is less than **0.04%**.

Geometry

The assembly geometry is modeled as explicitly as possible compared to Section 1.1 to 1.4. The axial detail is significant, including semi-explicit representation of the spacer grids, detailed axial reflector regions, including plenum, end plugs, and gaps. Reflective boundary conditions are applied on all radial sides. 50 cm of moderator are included above and below the core plates to include enough distance to properly calculate the neutron leakage.

The spacer grid representation is done as in problem 2Q, by dividing the grid mass equally amongst the 289 lattice cells, and placing that mass in an equivalent volume box on the outside of each cell. The spacer grid spacer sleeves are ignored.

The fission rate tallies are computed on a 49 level axial mesh, which represents approximately three inch regions and explicit resolution of spacer grid regions. This mesh is provided in Table P3-5, and in Appendix D.

Figure P3-1 provides a 3D graphical view of problem 3A, using KENO-3D.
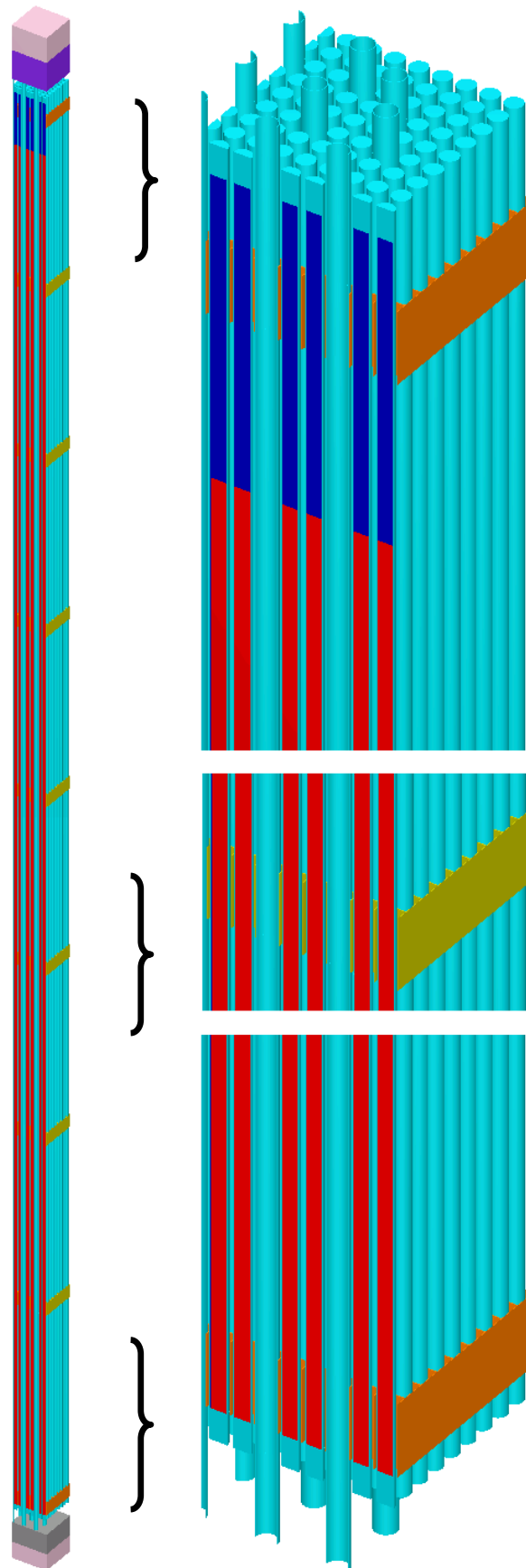
Figure P3-2: Problem 3 Reference Model

Input File

The input for this problem is over 54,000 lines long, so it is excluded from this document. The files for these problems are currently located on cpile2.ornl.gov at **/home/agm/vera.**

Computer Code

The reference calculations were executed with SCALE 6.2 Beta 2 on the Fission supercomputer at Idaho National Laboratory. The approximate run time was 5 days on 240 cores, utilizing up to 4 GB of memory per core.

Mixing Table

The following table provides the precise isotopic number densities used for each mixture in the reference problems.

Table P3-3: Reference Mixing Table

Material	Isotope ID	Atom Density (/barn-cm)
3.10% Fuel (3A)	8016	4.57642E-02
	92234	6.11864E-06
	92235	7.18132E-04
	92236	3.29861E-06
	92238	2.21546E-02
2.619% Fuel (3B)	8016	4.57617E-02
	92234	5.09503E-06
	92235	6.06733E-04
	92236	2.76809E-06
	92238	2.22663E-02
Gap	2004	2.68714E-05
Cladding & Zircaloy Grids	24050	3.30121E-06
	24052	6.36606E-05
	24053	7.21860E-06
	24054	1.79686E-06
	26054	8.68307E-06
	26056	1.36306E-04
	26057	3.14789E-06
	26058	4.18926E-07
	40090	2.18865E-02
	40091	4.77292E-03
	40092	7.29551E-03
	40094	7.39335E-03
	40096	1.19110E-03
	50112	4.68066E-06
	50114	3.18478E-06
	50115	1.64064E-06
	50116	7.01616E-05
	50117	3.70592E-05
	50118	1.16872E-04
	50119	4.14504E-05
	50120	1.57212E-04
	50122	2.23417E-05
	50124	2.79392E-05
	72174	3.54138E-09
	72176	1.16423E-07
	72177	4.11686E-07
	72178	6.03806E-07
	72179	3.01460E-07
	72180	7.76449E-07

Material	Isotope ID	Atom Density
1300 ppm Moderator (3A)	1001	4.96224E-02
	5010	1.07070E-05
	5011	4.30971E-05
	8016	2.48112E-02
1066 ppm Moderator (3B)	1001	4.96340E-02
	5010	8.77976E-06
	5011	3.53397E-05
	8016	2.48170E-02
Inconel	14028	4.04885E-03
	14029	2.05685E-04
	14030	1.35748E-04
	22046	2.12518E-04
	22047	1.91652E-04
	22048	1.89901E-03
	22049	1.39360E-04
	22050	1.33435E-04
	24050	6.18222E-04
	24052	1.19218E-02
	24053	1.35184E-03
	24054	3.36501E-04
	26054	3.61353E-04
	26056	5.67247E-03
	26057	1.31002E-04
	26058	1.74340E-05
	28058	4.17608E-02
	28060	1.60862E-02
	28061	6.99255E-04
	28062	2.22953E-03
	28064	5.67796E-04
Pyrex (3B)	5010	9.63266E-04
	5011	3.90172E-03
	8016	4.67761E-02
	14028	1.81980E-02
	14029	9.24474E-04
	14030	6.10133E-04
SS304 (3B)	6000	3.20895E-04
	14028	1.58197E-03
	14029	8.03653E-05
	14030	5.30394E-05
	15031	6.99938E-05
	24050	7.64915E-04
	24052	1.47506E-02
	24053	1.67260E-03

Isotope ID	Number Density
24054	4.16346E-04
25055	1.75387E-03
26054	3.44776E-03
26056	5.41225E-02
26057	1.24992E-03
26058	1.66342E-04

Isotope ID	Number Density
28058	5.30854E-03
28060	2.04484E-03
28061	8.88879E-05
28062	2.83413E-04
28064	7.21770E-05

Isotope ID	Top Nozzle 3A	Top Nozzle 3B	Bottom Nozzle 3A	Bottom Nozzle 3B	Core Plates 3A	Core Plates 3B
1001	4.01211E-02	4.01305E-02	3.57661E-02	3.57744E-02	2.48112E-02	2.48171E-02
5010	8.65222E-06	7.09198E-06	7.70514E-06	6.32374E-06	5.33040E-06	4.40970E-06
5011	3.48263E-05	2.85461E-05	3.10142E-05	2.54539E-05	2.14555E-05	1.77496E-05
6000	6.14459E-05	6.14459E-05	8.96008E-05	8.96008E-05	1.60447E-04	1.60447E-04
8016	2.00606E-02	2.00653E-02	1.78830E-02	1.78872E-02	1.24056E-02	1.24085E-02
14028	3.02920E-04		4.41720E-04		7.90985E-04	
14029	1.53886E-05		2.24397E-05		4.01826E-05	
14030	1.01561E-05		1.48097E-05		2.65197E-05	
15031	1.34026E-05		1.95438E-05		3.49969E-05	
24050	1.46468E-04		2.13581E-04		3.82458E-04	
24052	2.82449E-03		4.11869E-03		7.37532E-03	
24053	3.20275E-04		4.67027E-04		8.36302E-04	
24054	7.97232E-05		1.16253E-04		2.08173E-04	
25055	3.35836E-04		4.89719E-04		8.76936E-04	
26054	6.60188E-04		9.62690E-04		1.72388E-03	
26056	1.03635E-02		1.51122E-02		2.70613E-02	
26057	2.39339E-04		3.49006E-04		6.24963E-04	
26058	3.18517E-05		4.64463E-05		8.31710E-05	
28058	1.01650E-03		1.48226E-03		2.65427E-03	
28060	3.91552E-04		5.70964E-04		1.02242E-03	
28061	1.70205E-05		2.48194E-05		4.44439E-05	
28062	5.42688E-05		7.91351E-05		1.41707E-04	
28064	1.38207E-05		2.01534E-05		3.60885E-05	

REFERENCE SOLUTION RESULTS

The eigenvalues calculated by CE KENO-VI for the reference cases are provided below.

Table P3-4: Problem 3 Reference Solution Results

Problem	Description	Enrichment	Boron	Temperature	k-effective	Axial Offset
3A	No Poisons	3.10%	1300 ppm	600K	**1.175722 ± 0.000005**	0.163%
3B	16 Pyrex	2.619%	1066 ppm	565K	**1.000154 ± 0.000006**	-0.062%

The individual pin powers are too large to include in this document. They can be obtained by request from the author at godfreyat@ornl.gov . Summary results for the radial and axial power shapes are provided below, and in Appendix D in ASCII form.
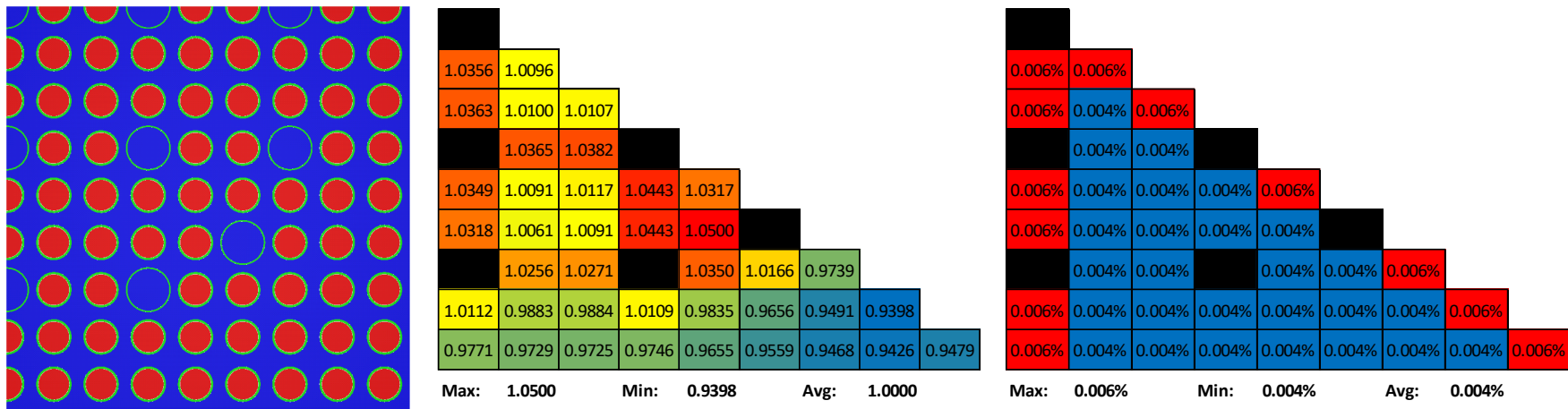
Figure P3-3: Problem 3A CE KENO-VI Radial Power Distribution Results
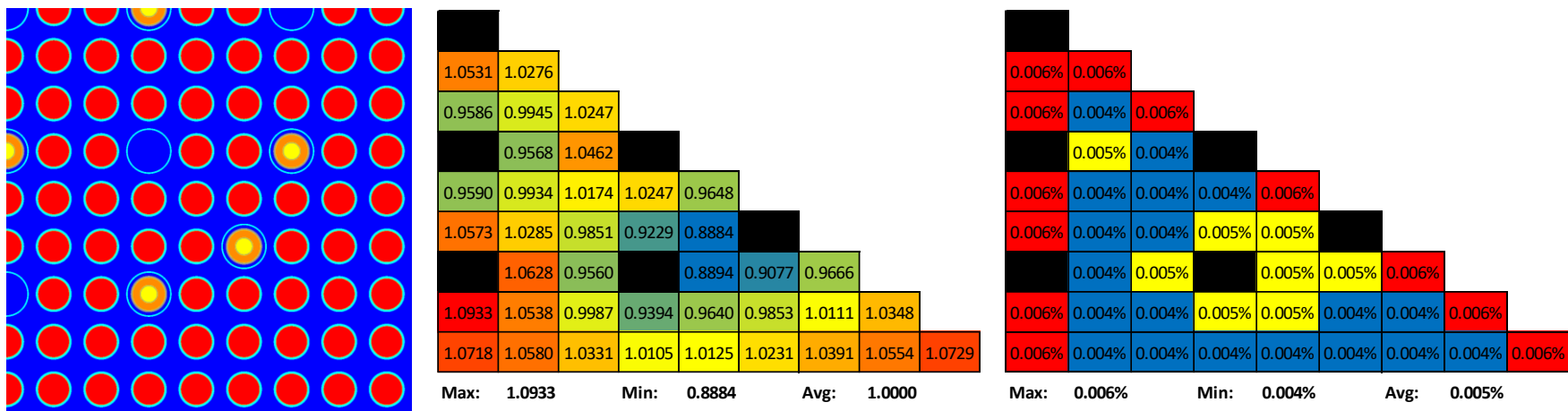
Figure P3-4: Problem 3B CE KENO-VI Radial Power Distribution Results

Table P3-5: CE KENO-VI Axial Power Distributions†

Level	Elevation (cm)	Thickness (cm)	3A	3B
49	377.711	7.9212	0.17166	0.18312
48	369.7898	7.9212	0.24941	0.25469
47	361.8686	7.9212	0.34668	0.35096
46	353.9474	7.9212	0.44235	0.44547
45	346.0262	7.9212	0.53052	0.53161
44	338.105	3.81	0.56887	0.56589
43	334.295	8.065	0.66502	0.66528
42	326.23	8.065	0.75936	0.76009
41	318.165	8.065	0.84438	0.84472
40	310.1	8.065	0.92588	0.92521
39	302.035	8.065	1.00378	1.00166
38	293.97	8.065	1.06708	1.06193
37	285.905	3.81	1.06292	1.05119
36	282.095	8.065	1.16570	1.16009
35	274.03	8.065	1.23691	1.23312
34	265.965	8.065	1.29183	1.28808
33	257.9	8.065	1.34148	1.33725
32	249.835	8.065	1.38579	1.38059
31	241.77	8.065	1.41065	1.40262
30	233.705	3.81	1.36407	1.34781
29	229.895	8.065	1.45468	1.44648
28	221.83	8.065	1.48986	1.48459
27	213.765	8.065	1.50467	1.50024
26	205.7	8.065	1.51357	1.50921
25	197.635	8.065	1.51653	1.51133
24	189.57	8.065	1.49862	1.49098
23	181.505	3.81	1.41795	1.40185
22	177.695	8.065	1.47993	1.47282
21	169.63	8.065	1.47284	1.46893
20	161.565	8.065	1.44481	1.44265
19	153.5	8.065	1.41136	1.40950
18	145.435	8.065	1.37204	1.37027
17	137.37	8.065	1.31438	1.31074
16	129.305	3.81	1.21448	1.20371
15	125.495	8.065	1.23644	1.23397
14	117.43	8.065	1.18801	1.18879
13	109.365	8.065	1.12254	1.12492
12	101.3	8.065	1.05270	1.05613
11	93.235	8.065	0.97853	0.98264
10	85.17	8.065	0.89182	0.89532
9	77.105	3.81	0.79068	0.78969
8	73.295	8.2111	0.76820	0.77329
7	65.0839	8.2112	0.68569	0.69336
6	56.8727	8.2111	0.59265	0.60190
5	48.6616	8.2112	0.49716	0.50769
4	40.4504	8.2111	0.39929	0.41069
3	32.2393	8.2112	0.29915	0.31134
2	24.0281	8.2111	0.19703	0.21087
1	15.817	3.866	0.13945	0.16628
0	11.951			

†Maximum uncertainty in radially-integrated power is 0.014%
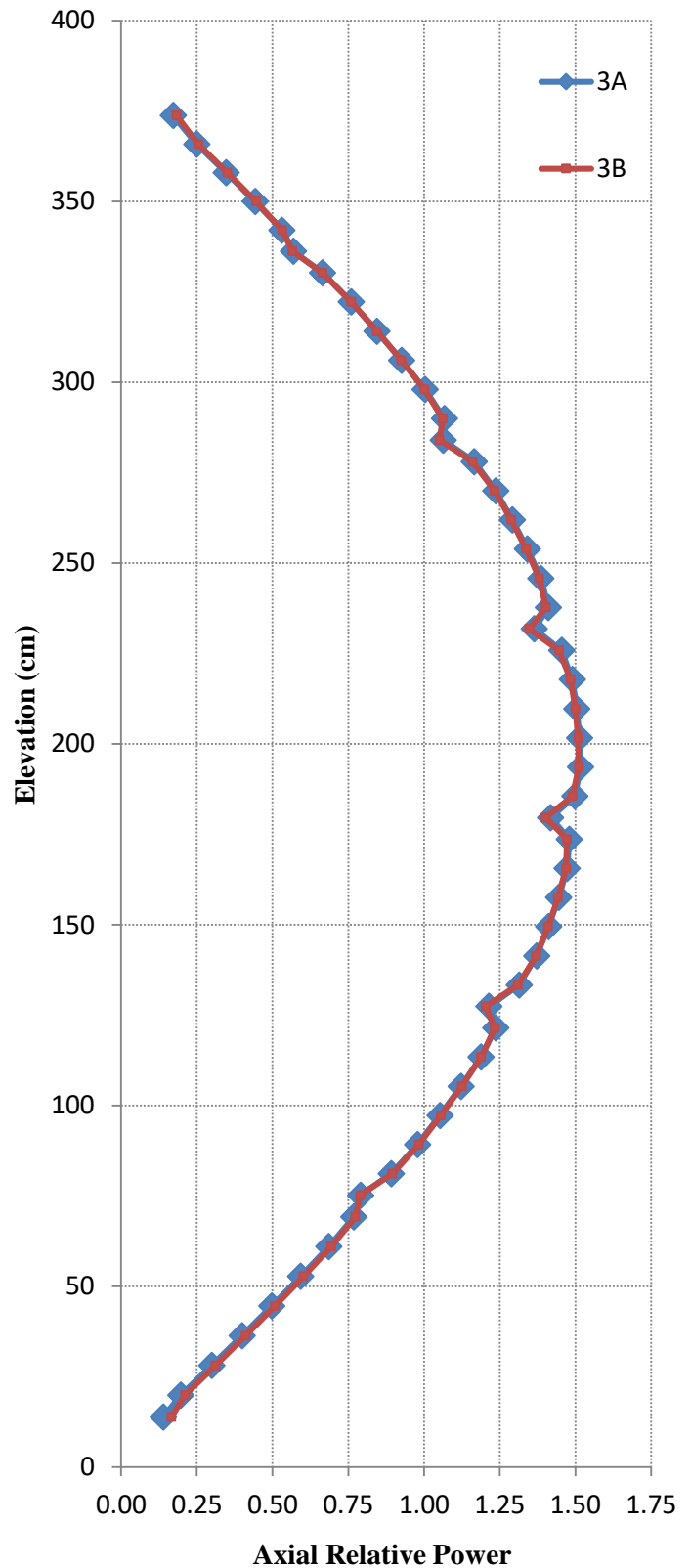
Figure P3-5: Problem 3 Axial Powers

Problem #4: 3D HZP 3x3 Assembly Control Rod Worth

PURPOSE

The fourth VERA core physics benchmark progression problem builds on the 3D assembly problem by the addition of multiple assemblies and RCCAs. Successful completion demonstrates the capability to predict the eigenvalue and pin power distribution without thermal-hydraulic feedback or depletion in the presence of black neutron absorbers. Furthermore, this problem permits a detailed study of methods accuracy and convergence capability for a region of an actual reactor core, and is the first chance to perform RCCA movement and calculate a control rod reactivity worth, a critical reactor physics parameter which is often used for validation of nuclear methods.

SPECIFICATIONS

The problem consists of nine Westinghouse 17x17-type fuel assemblies arranged in a 3x3 checkerboard pattern directly from the center of the WBN1 initial loading pattern (Sections 1.1 to 1.7 and Section 1.12). The fuel is at beginning-of-life (BOL) and Hot Zero Power (HZP) isothermal conditions. In addition to the same materials as Problem 3, this problem also tests the ability to define and place Pyrex (1.5), AIC, and B_4C (1.6) absorbers in the assembly guide tubes, as well as position the RCCA by simply providing the number of steps withdrawn for the bank.

Figure P4-1 provides the loading pattern for this problem, simply from the center of the WBN1 core described in Section 1.12 and Reference 1. In this figure, Region 1 is represented by the 2.11% enrichment with center RCCA, and Region 2 is the 2.619% enriched region with 20 Pyrex rods. The hybrid AIC/B_4C RCCA is located in the center assembly. This problem is ideally run in quarter or octant symmetry.
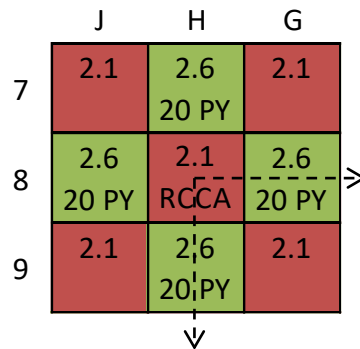
Figure P4-1: Problem 4 Assembly, Poison, and Control Layout

The reference cases for Problem 4 involve a series of different control rod positions. The first case has the bottom of the RCCA poison at a discrete position of **259.7 cm**, relative to the top of the bottom core plate. This position is precisely between two spacer grids and is also an axial mesh boundary in the reference solution, and was chosen for being close to the initial critical position of WBN1. The other eleven cases for Problem 4 are for RCCA positions spanning fully inserted to fully withdrawn at 10% increments, based on the RCCA drive characteristics provided in Table 8. From these cases, differential and integral control rod worths can be calculated and compared to the reference.

Table P4-1: Problem 4 Input Specification

Input	Value	Section
Fuel Density	10.257 g/cc	2.2
Fuel Enrichment – Region 1	2.11%	2.1
Fuel Enrichment – Region 2	2.619%	2.1
Power	0% FP	--
Inlet Coolant Temperature	565 K	--
Inlet Coolant Density	0.743 g/cc	2.0
Reactor Pressure	2250 psia	3.
Boron Concentration	1360 ppm	--

- The fuel enrichments are directly from the as-built values from the WBN1 initial loading (Reference 1).
- The fuel density is chosen to account for dishes and chamfers in the pellet stack as described in Section 2.2.
- The moderator density corresponds to 565K at the core pressure. (Reference 4).
- The 20 Pyrex pattern (Section 1.5) uses 4 thimble plugs (Section 1.7) in the remaining empty guide tubes, though this is not likely to affect the neutronics solution significantly. In addition, the corner assemblies also include 24 thimble plugs since those guide tubes contain neither Pyrex or RCCA rodlets.
- The boron concentration of 1360 is used to make the first Problem 4 case close to critical.

MATERIAL PROPERTIES

All material properties are listed in Section 2.

CAPABILITIES

Successful completion of this benchmark problem can be used to demonstrate the following capabilities:

- Definition and placement of discrete burnable poison clusters
- Definition, placement, and automatic axial positioning of control rods (RCCAs)
- Definition and layout of multiple assembly types
- Definition of multiple control rod materials in a single rod type
- Account for control rod tip or material boundary which does not lie on a mesh boundary
- Perform cross section treatment on non-fuel absorbers such as poisons and control rods
- Account for effects of immediate control rod poison on local cross section processing
- Account for "thin plane" effects due to minor axial differences between fuel, poisons, and control rods
- Account for different axial mesh needs in different assemblies
- Provide capability of performing multiple, dependent cases, with rod movements
- Output of problem average radial and axial relative power distributions
- Validate differential control rod worth against CE Monte Carlo calculations
- Provide visualization of 3D flux/power suppression near the control rod tips

REFERENCE SOLUTION

The reference values for this benchmark problem are calculated by the SCALE 6.2 Beta (Ref. 6) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The CSAS6

sequence for KENO-VI uses input that includes materials, densities, fuel isotopics, an exact geometry description, and other code options. For this problem, KENO-VI can provide an approximate eigenvalue solution within a small range of uncertainty using the precise geometry specification. It can also perform fission rate tallies for each fuel rod at each prescribed axial location, which has been normalized and post-processed to produce the pin power distribution as well as a distribution of uncertainties.

Due to problem size and detail, including semi-explicit spacer grids and the need for unique units for each power region, a FORTRAN computer code was created to create the input automatically based on a series of simple problem descriptors. This input is too large to include in this document (~450,000 lines). This code is located at **/home/agm/git/kenogen**.

Cross Sections

The reference solution is based on ENDF/B-VII.0 CE cross sections as obtained from SCALE 6.2 (**ce-v7-endf**) (Ref. 6). Only 565K cross sections are utilized. For the isotope H-1, the S(α,β) scattering data is not interpolated internally and is only available at 550K and 600K. Therefore a secondary calculation was performed and the final results include a manually calculated correction factor (-40 pcm).

Materials

The SCALE 6.2 material processor MIPLIB allows common input of compositions across most SCALE codes and sequences. For this problem, the materials are input nearly exactly as described in this specification, with the following exceptions:

- The fuel isotopes are calculated based on the equations in Table 17 (and Ref. 5) and are provided here.

Table P4-2: Problem 4 Calculated Isotopic Input

Isotope	Region 1 Wt%	Region 2 Wt%
U-234	0.0174%	0.0219%
U-235	2.11%	2.619%
U-236	0.0097%	0.0120%
U-238	97.8629%	97.3471%

*Note that explicit O-16 is not needed in MIPLIB input

- For the reference calculation, the pellet-clad gap is modeled explicitly as Helium with nominal density. This could also be modeled as 'void' or air.
- The boron concentration is input by use of weight fractions with the H_2O and boron MIPLIB compositions. For 1360 ppm, the corresponding weight fraction is 0.001360, and the water fraction is 0.998640.
- The material content for the top and bottom nozzles and top and bottom core plates was homogenized manually based on the material densities and heights. These materials are provided in the mixing table below.

Parameters

An extremely large number of particle histories is needed to get the power distribution uncertainty low enough to be useful for power distribution comparison with other codes, especially in the regions of lowest power. For the first case, 50e9 particle histories, using 10,000 generations with 5e6 particles per generation, skipping 500 generations, produces less than 0.4 pcm uncertainty in the eigenvalue and less than 0.065% uncertainty in average pin power. For the rod worth case, 1/10th of

these generations were used, only 5e9 particles (1000 generations, skipping 300), which resulted in an eigenvalue uncertainty of less than 1.5 pcm and a less than 0.25% uncertainty in average pin power (less than 3.9% maximum). More statistics and runtimes for these cases are provided in Table P4-5.

Geometry

The assembly geometry is modeled as explicitly as possible compared to Section 1.1 to 1.4. The axial detail is significant, including semi-explicit representation of the spacer grids, detailed axial reflector regions, including plenum, end plugs, and gaps. Reflective boundary conditions are applied on all radial sides. 50 cm of moderator are included above and below the core plates to include enough distance to properly calculate the neutron leakage.

The Pyrex and control rods are explicitly modeled and positioned as described in sections 1.5 and 1.6, and thimble plugs are placed in any empty guide tube as described in Section 1.7

The spacer grid representation is done as in Problem 2Q and Problem 3, by dividing the grid mass equally amongst the 289 lattice cells, and placing that mass in an equivalent volume in a box on the outside of each cell. The spacer grid spacer sleeves are ignored.

Figure P4-2 provides a radial view of a slice through the middle of the problem 4 geometry. Figure P4-3 provides an axial view. These are for the first case where the RCCA is partly inserted with the poison tip on a mesh boundary.

The fission rate tallies are computed on a 49 level axial mesh, which represents approximately three inch regions and explicit resolution of spacer grid regions. This mesh is provided in the Problem 3 results and in Appendix E.
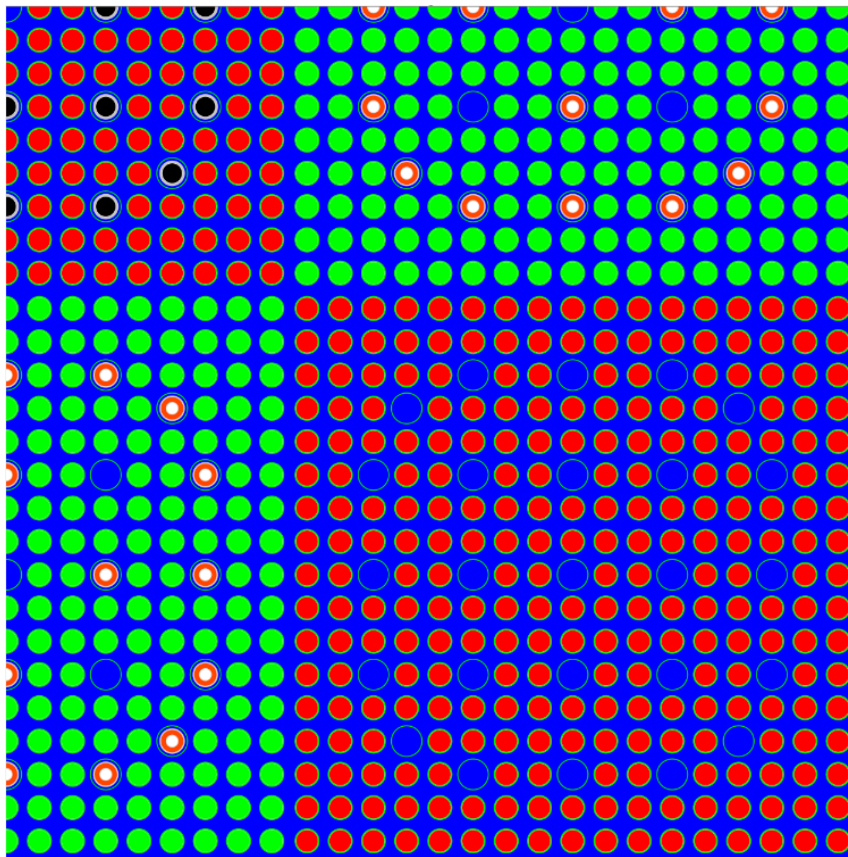
Figure P4-2: Problem 4 Radial KENO-VI Geometry
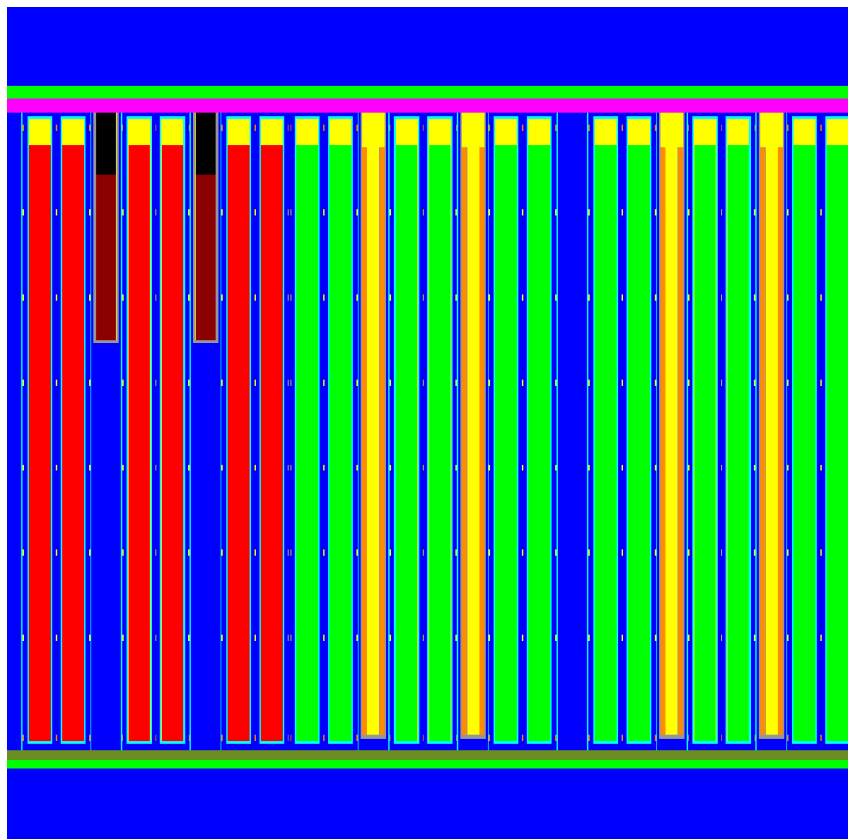
Figure P4-3: Problem 4 Axial KENO-VI Geometry (not to proportion)

Input File

The input for this problem is nearly 450,000 lines long, so it is excluded from this document. The files for these problems are currently located on cpile2.ornl.gov at **/home/agm/vera.**

Computer Code

The reference calculations were executed with SCALE 6.2 Beta 2 on the Fission supercomputer at Idaho National Laboratory. The approximate run time for the initial case was 11 days on 300 cores, utilizing up to 4.3 GB of memory per core. The rod worth cases took approximately 26 hours each, also on 300 cores and up to 4.3 GB of memory per core. See Table P4-5 for more information.

Mixing Table

The following table provides the precise isotopic number densities used for each mixture in the reference problems.

Table P4-3: Reference Mixing Table

Material	Isotope ID	Atom Density (/barn-cm)
2.11% Fuel	8016	4.57591E-02
	92234	4.04814E-06
	92235	4.88801E-04
	92236	2.23756E-06
	92238	2.23844E-02
2.619% Fuel	8016	4.57617E-02
	92234	5.09503E-06
	92235	6.06733E-04
	92236	2.76809E-06
	92238	2.22663E-02
Gap	2004	2.68714E-05
Cladding & Zircaloy Grids	24050	3.30121E-06
	24052	6.36606E-05
	24053	7.21860E-06
	24054	1.79686E-06
	26054	8.68307E-06
	26056	1.36306E-04
	26057	3.14789E-06
	26058	4.18926E-07
	40090	2.18865E-02
	40091	4.77292E-03
	40092	7.29551E-03
	40094	7.39335E-03
	40096	1.19110E-03
	50112	4.68066E-06
	50114	3.18478E-06
	50115	1.64064E-06
	50116	7.01616E-05
	50117	3.70592E-05
	50118	1.16872E-04
	50119	4.14504E-05
	50120	1.57212E-04
	50122	2.23417E-05
	50124	2.79392E-05
	72174	3.54138E-09
	72176	1.16423E-07
	72177	4.11686E-07
	72178	6.03806E-07
	72179	3.01460E-07

Material	Isotope ID	Atom Density (/barn-cm)
	72180	7.76449E-07
1360 ppm Moderator	1001	4.96194E-02
	5010	1.12012E-05
	5011	4.50862E-05
	8016	2.48097E-02
Inconel	14028	4.04885E-03
	14029	2.05685E-04
	14030	1.35748E-04
	22046	2.12518E-04
	22047	1.91652E-04
	22048	1.89901E-03
	22049	1.39360E-04
	22050	1.33435E-04
	24050	6.18222E-04
	24052	1.19218E-02
	24053	1.35184E-03
	24054	3.36501E-04
	26054	3.61353E-04
	26056	5.67247E-03
	26057	1.31002E-04
	26058	1.74340E-05
	28058	4.17608E-02
	28060	1.60862E-02
	28061	6.99255E-04
	28062	2.22953E-03
	28064	5.67796E-04
Top Nozzle	1001	4.01187E-02
	5010	9.05410E-06
	5011	3.64439E-05
	6000	6.14459E-05
	8016	2.00593E-02
	14028	3.02920E-04
	14029	1.53886E-05
	14030	1.01561E-05
	15031	1.34026E-05
	24050	1.46468E-04
	24052	2.82449E-03
	24053	3.20275E-04
	24054	7.97232E-05
	25055	3.35836E-04
	26054	6.60188E-04
	26056	1.03635E-02
	26057	2.39339E-04

Material	Isotope	Value	Material	Isotope	Value
	26058	3.18517E-05	Pyrex	5010	9.63266E-04
	28058	1.01650E-03		5011	3.90172E-03
	28060	3.91552E-04		8016	4.67761E-02
	28061	1.70205E-05		14028	1.81980E-02
	28062	5.42688E-05		14029	9.24474E-04
	28064	1.38207E-05		14030	6.10133E-04
Bottom Nozzle	1001	3.57638E-02	SS304	6000	3.20895E-04
	5010	8.07351E-06		14028	1.58197E-03
	5011	3.24969E-05		14029	8.03653E-05
	6000	8.96008E-05		14030	5.30394E-05
	8016	1.78819E-02		15031	6.99938E-05
	14028	4.41720E-04		24050	7.64915E-04
	14029	2.24397E-05		24052	1.47506E-02
	14030	1.48097E-05		24053	1.67260E-03
	15031	1.95438E-05		24054	4.16346E-04
	24050	2.13581E-04		25055	1.75387E-03
	24052	4.11869E-03		26054	3.44776E-03
	24053	4.67027E-04		26056	5.41225E-02
	24054	1.16253E-04		26057	1.24992E-03
	25055	4.89719E-04		26058	1.66342E-04
	26054	9.62690E-04		28058	5.30854E-03
	26056	1.51122E-02		28060	2.04484E-03
	26057	3.49006E-04		28061	8.88879E-05
	26058	4.64463E-05		28062	2.83413E-04
	28058	1.48226E-03		28064	7.21770E-05
	28060	5.70964E-04	B4C	5010	1.52689E-02
	28061	2.48194E-05		5011	6.14591E-02
	28062	7.91351E-05		6000	1.91820E-02
	28064	2.01534E-05	AIC	47107	2.36159E-02
Core Plates	1001	2.48098E-02		47109	2.19403E-02
	5010	5.62115E-06		48106	3.41523E-05
	5011	2.26258E-05		48108	2.43165E-05
	6000	1.60447E-04		48110	3.41250E-04
	8016	1.24049E-02		48111	3.49720E-04
	14028	7.90985E-04		48112	6.59276E-04
	14029	4.01826E-05		48113	3.33873E-04
	14030	2.65197E-05		48114	7.84957E-04
	15031	3.49969E-05		48116	2.04641E-04
	24050	3.82458E-04		49113	3.44262E-04
	24052	7.37532E-03		49115	7.68050E-03
	24053	8.36302E-04			
	24054	2.08173E-04			
	25055	8.76936E-04			
	26054	1.72388E-03			
	26056	2.70613E-02			
	26057	6.24963E-04			
	26058	8.31710E-05			
	28058	2.65427E-03			
	28060	1.02242E-03			
	28061	4.44439E-05			
	28062	1.41707E-04			
	28064	3.60885E-05			

REFERENCE SOLUTION RESULTS

The eigenvalues calculated by CE KENO-VI for the reference cases are provided below, along with the differential (DRW) and integral (IRW) control rod reactivity worths, calculated by:

$$\rho_{CRD} = \left(1/k_{UNC} - 1/k_{CON} \right) \times 10^5 \; [pcm]$$

Table P4-4: Problem 4 Reference Solution Results

Rod Position	% Withdrawn	k-effective	DRW (± 2 pcm)	IRW (± 2 pcm)	Axial Offset (%)
257.9 cm	--	0.998981 ± 0.000005	--	-240	-35.3
0 steps	0%	0.972411 ± 0.000015	-134	-2975	-6.9
23 steps	10%	0.973679 ± 0.000014	-596	-2842	-20.9
46 steps	20%	0.979363 ± 0.000016	-794	-2245	-56.5
69 steps	30%	0.987043 ± 0.000015	-541	-1451	-71.6
92 steps	40%	0.992341 ± 0.000014	-344	-910	-70.9
115 steps	50%	0.995745 ± 0.000014	-230	-566	-62.0
138 steps	60%	0.998028 ± 0.000015	-153	-336	-45.8
161 steps	70%	0.999551 ± 0.000013	-103	-183	-28.5
184 steps	80%	1.000584 ± 0.000013	-58	-80	-13.6
207 steps	90%	1.001168 ± 0.000013	-22	-22	-3.0
230 steps	100%	1.001385 ± 0.000013	--	--	0.0

In each of these cases, a -40 pcm correction has been applied for the use of 550K scattering data for H-1. Figures of these DRW and IRW results are shown in Figure P4-7 and P4-8. Table P4-5 provides a summary of the statistical uncertainties for the calculated power distributions.

Table P4-5: Problem 4 Monte Carlo Statistics

	Base Case	Rod Worth Cases
Total # Particles	50e9	5e9
# Particles / Generation	5e6	5e6
# Generations	10,000	1,000
# Skipped Generations	500	300
# Cores	300	300
Memory / Core	4.3 GB	4.3 GB
Runtime	11 days	26 hours
Eigenvalue Uncertainty	± 0.35 pcm	< ± 1.5 pcm
Average Pin Power Uncertainty	± 0.065%	< ± 0.243%
Maximum Pin Power Uncertainty (by Power)	Power < 1.0: ± 0.705% Power > 1.0: ± 0.124%	Power < 1.0: < ± 3.883% Power > 1.0: < ± 0.486%

The individual pin powers are too large to include in this document. They can be obtained by request from the author at godfreyat@ornl.gov . Summary results for the radial and axial power shapes for the main problem (with the RCCA at 257.9 cm) are provided below.
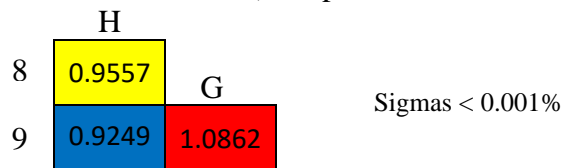
Figure P4-4: Problem 4 CE KENO-VI Radial Assembly Powers (octant)
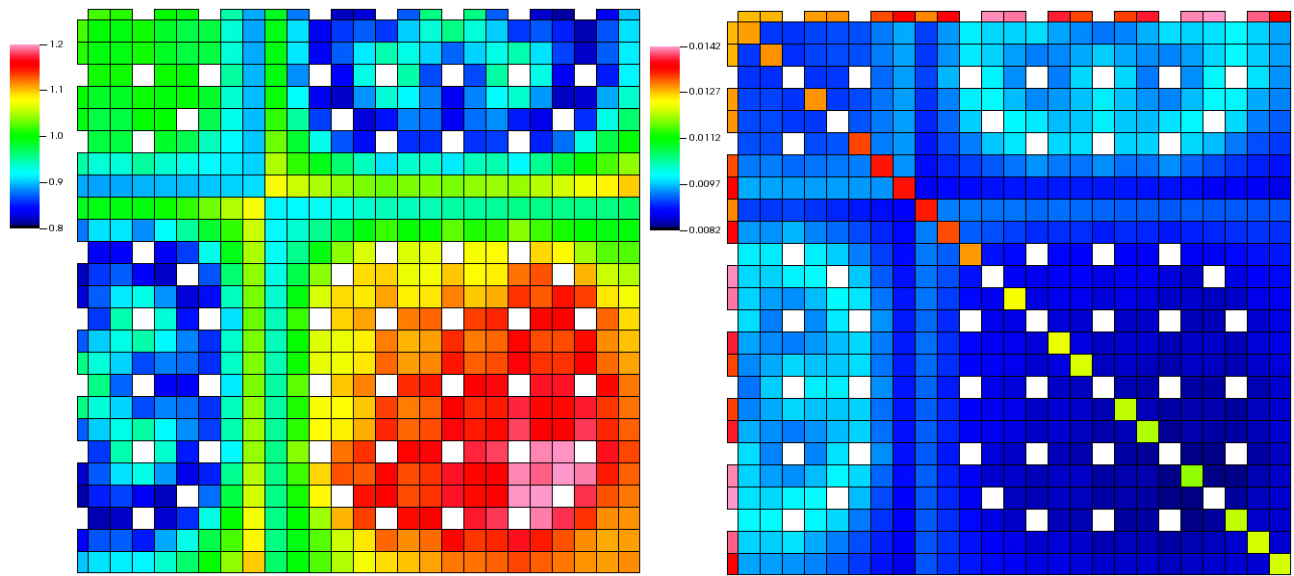
Figure P4-5: Problem 4 CE KENO-VI Radial Power Distribution and Uncertainty (%)
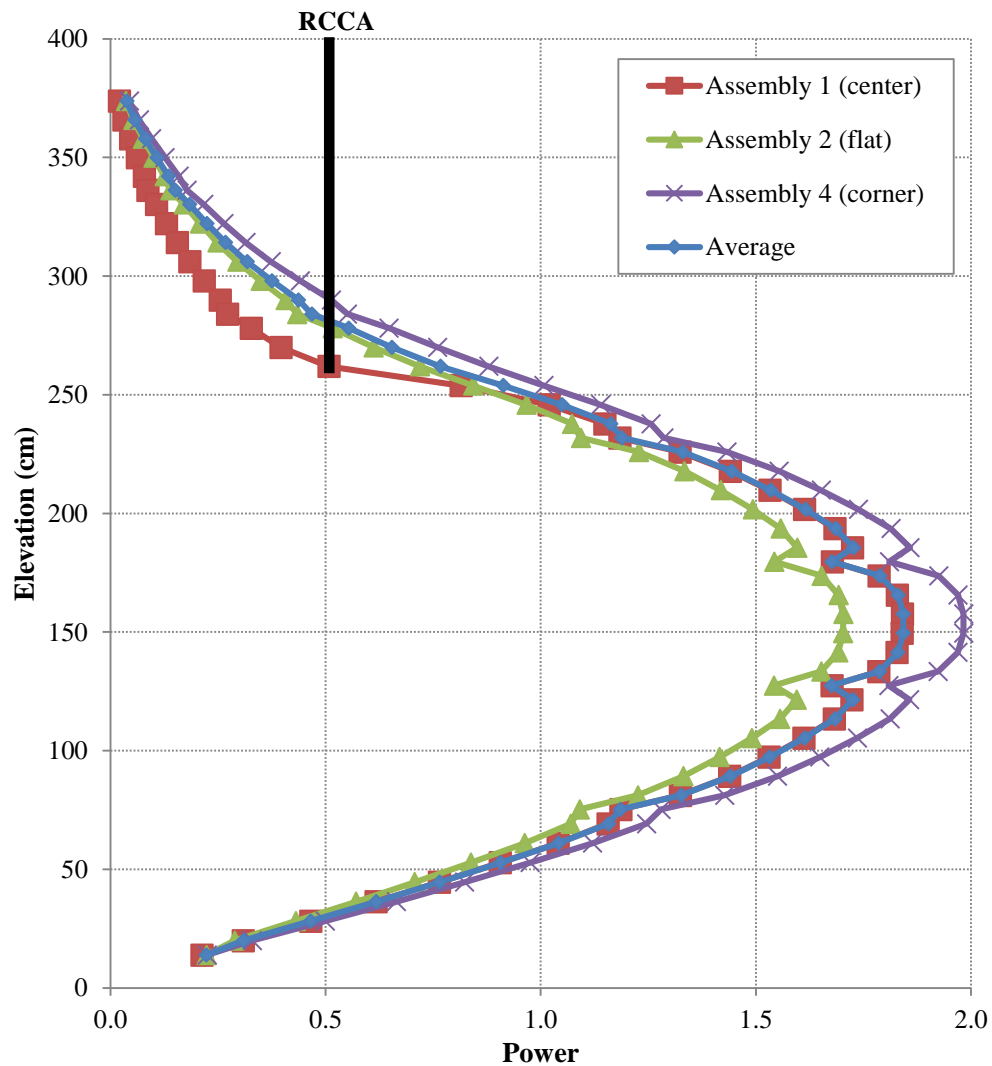
Figure P4-6: Problem 4 CE KENO-VI Average Axial Power Distributions
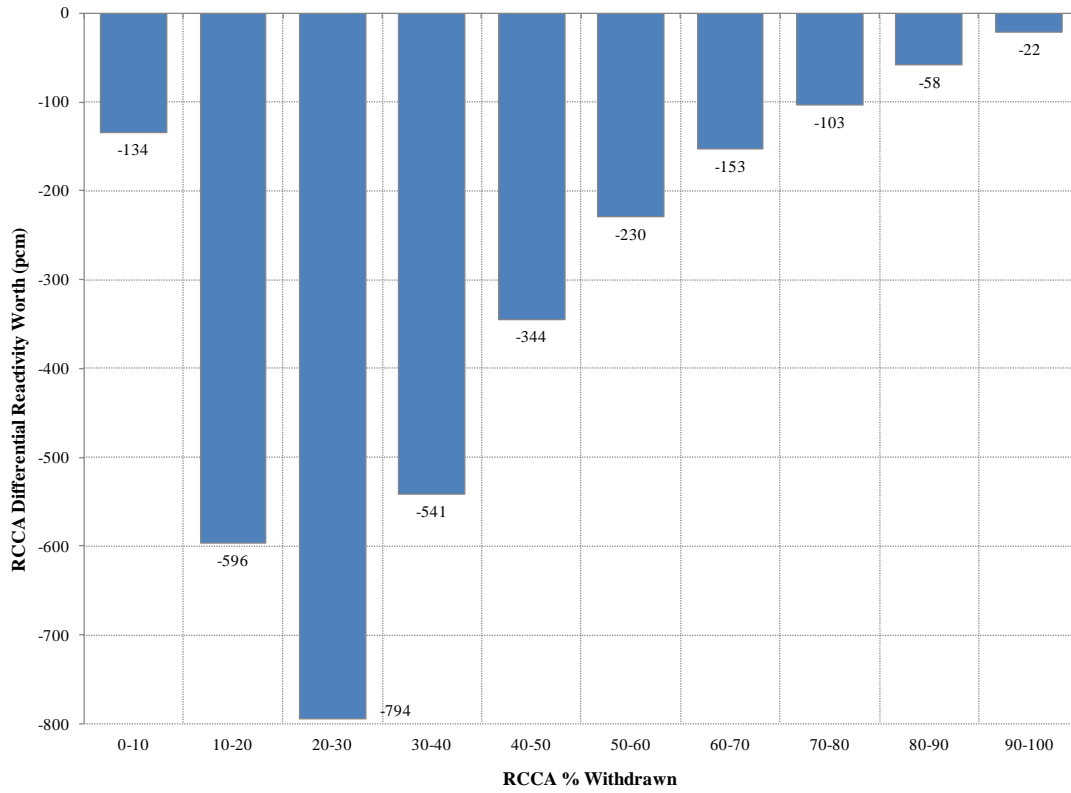
Figure P4-7: Problem 4 CE KENO-VI Differential Control Rod Worths
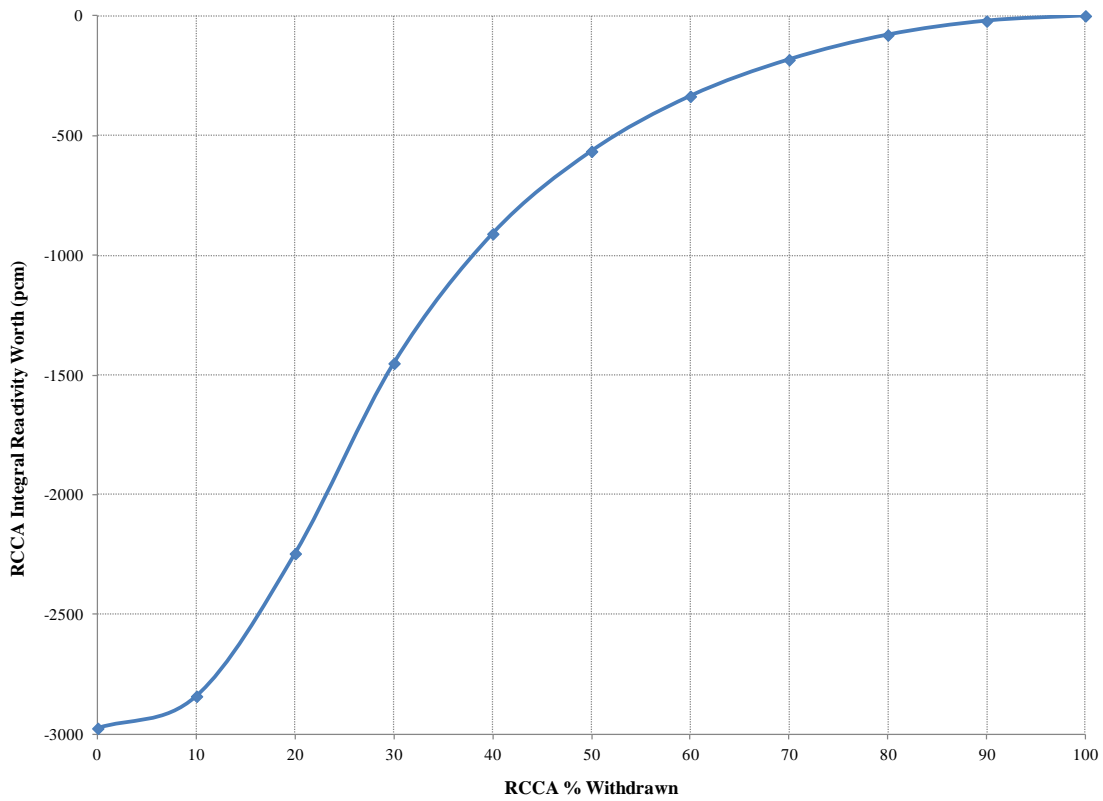
Figure P4-8: Problem 4 CE KENO-VI Integral Control Rod Worth Curve
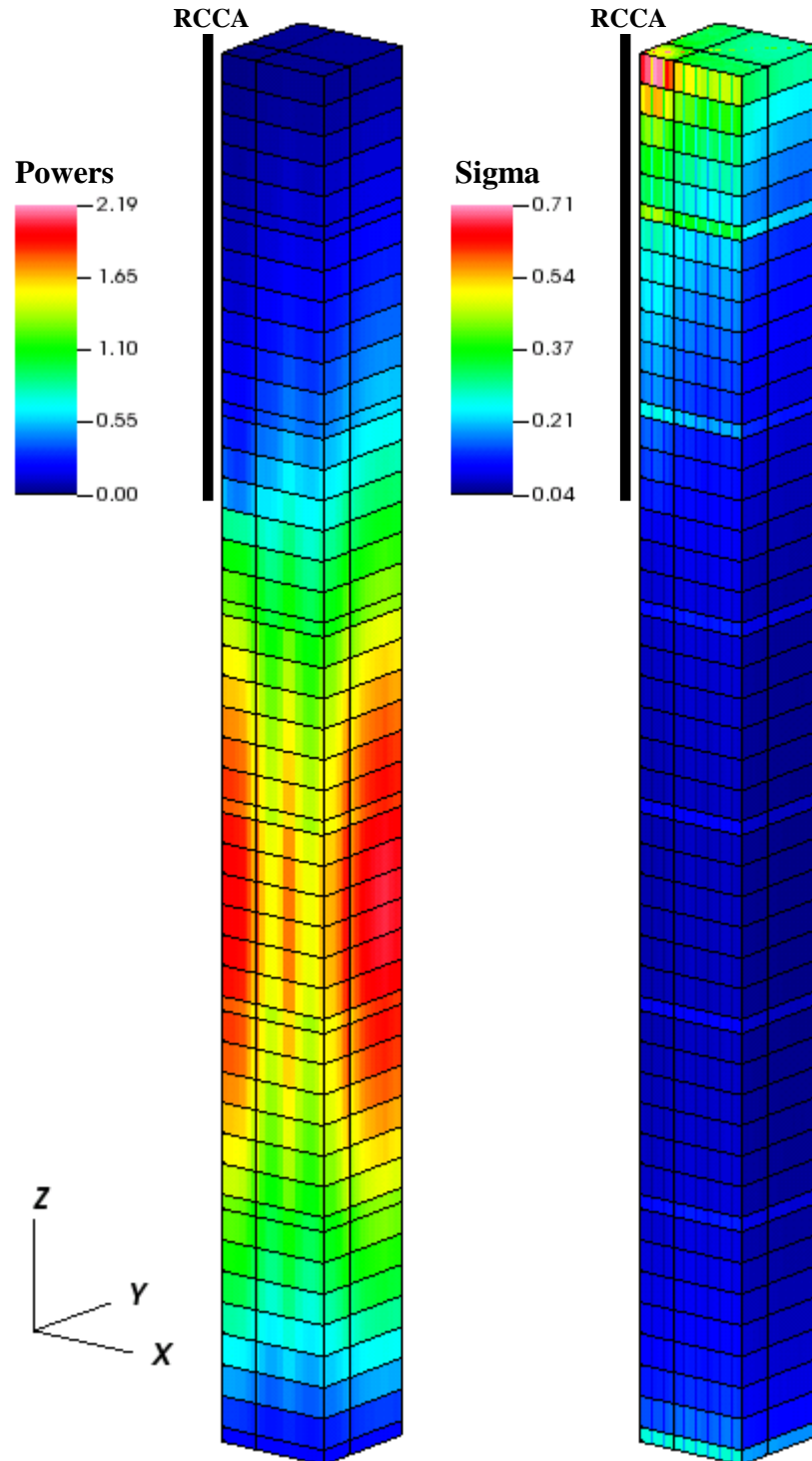
Figure P4-9: Problem 4 CE KENO-VI 3D Fission Rate Distribution and Uncertainties (%)

Problem #5: Physical Reactor Zero Power Physics Tests

PURPOSE

The fifth VERA core physics benchmark progression problem expands the test suite to a full reactor model consistent with typical nuclear core analysis. Successful completion demonstrates the capability to predict the eigenvalue and core reactivity coefficients without thermal-hydraulic feedback or depletion. The goal of this problem is to successfully perform the calculations associated with the Zero Power Physics Tests (ZPPT) that are performed at the beginning of each fuel cycle startup. These include predictions of several critical configurations, the RCCA bank reactivity worths, the isothermal temperature reactivity coefficient (ITC), and the differential soluble boron worth (DBW). This is also the first progression problem that provides the opportunity to compare to measured startup data from WBN1.

SPECIFICATIONS

The problem consists of a full core of Westinghouse 17x17-type fuel assemblies in the WBN1 initial loading pattern (Sections 1.1 to 1.7 and Section 1.12). All fuel is at beginning-of-life (BOL) and Hot Zero Power (HZP) isothermal conditions. In addition to the specification of Problem 4, this problem also tests the ability to define RCCA Banks and move them independently, and define and place incore instrumentation thimble tubes.

Figure P4-1 provides the loading pattern for this problem, as described in Section 1.12 and Reference 1. In this figure, Region 1 is represented by the 2.11% enrichment, Region 2 is the 2.619% enriched region, and Region 3 is 3.10% enriched. Figures 9 through 12 provide the specifications for the full core layout for control banks, instruments, and radial support structures. This problem is ideally run in quarter symmetry, but the instrumentation does not have symmetry.

Left map (Enrichment / Number of Pyrex Rods):

	H	G	F	E	D	C	B	A
8	2.1	2.6 20	2.1	2.6 20	2.1	2.6 20	2.1	3.1 12
9	2.6 20	2.1	2.6 24	2.1	2.6 20	2.1	3.1 24	3.1
10	2.1	2.6 24	2.1	2.6 20	2.1	2.6 16	2.1	3.1 8
11	2.6 20	2.1	2.6 20	2.1	2.6 20	2.1	3.1 16	3.1
12	2.1	2.6 20	2.1	2.6 20	2.6	2.6 24	3.1	
13	2.6 20	2.1	2.6 16	2.1	2.6 24	3.1 12	3.1	
14	2.1	3.1 24	2.1	3.1 16	3.1	3.1		
15	3.1 12	3.1	3.1 8	3.1	Enrichment / Number of Pyrex Rods			

Right map (Poison and Control Rod Layout):

	H	G	F	E	D	C	B	A
8	D		A		D		C	
9							SB	
10	A		C				B	
11				A		SC		
12	D				D		SA	
13		SB		SD				
14	C		B		SA			
15								

Figure P5-1: Problem 5 Assembly, Poison, and Control Rod Layout
(Quarter Symmetry)

The reference cases for Problem 5 are a variety of different control rod bank positions, soluble boron concentrations, and temperatures consistent with the actual WBN1 Cycle 1 ZPPTs. The detailed specification for the cases is provided in Table P5-2. Bank positions relative to the bottom core plate are calculated from the information in Table 8 as:

$$bank\ position\ (cm) = 17.031 + steps \times 1.5875$$

Table P5-1: Problem 5 Initial Criticality Input Specification

Input	Value	Section
Fuel Density	10.257 g/cc	2.2
Fuel Enrichment – Region 1	2.11%	2.1
Fuel Enrichment – Region 2	2.619%	2.1
Fuel Enrichment – Region 3	3.10%	2.1
Power	0% FP	--
Inlet Coolant Temperature	565 K	--
Inlet Coolant Density	0.743 g/cc	2.0
Reactor Pressure	2250 psia	3.
Initial Boron Concentration	1285 ppm	3.
Initial Critical Bank D Position	167 steps	--

- The fuel enrichments are directly from the as-built values from the WBN1 initial loading (Reference 1).
- The fuel density is chosen to account for dishes and chamfers in the pellet stack as described in Section 2.2.
- The moderator temperature and density correspond to 565K at the core pressure (Reference 4).
- The initial critical boron concentration is the measured value from WBN1C1 adjusted to 19.9 at% B-10 concentration (Reference 16).
- The initial critical Bank D position is the measured value from WBN1C1, for which criticality was obtained on Bank D withdrawal while the other banks were already fully withdrawn.

Table P5-2: Problem 5 Cases for WBN1 ZPPT

Case	Boron (ppm)	Temp (K)	A	B	C	D	SA	SB	SC	SD	Description	
1	1285	565	-	-	-	167	-	-	-	-	Initial	
2	1291	↓	-	-	-	-	-	-	-	-	ARO	
3	1170	↓	0	-	-	97	-	-	-	-	Bank A	
4	↓	↓	-	0	-	113	-	-	-	-	Bank B	
5	↓	↓	-	-	0	119	-	-	-	-	Bank C	Criticals
6	↓	↓	-	-	-	18	-	-	-	-	Bank D	
7	↓	↓	-	-	-	69	0	-	-	-	Bank SA	
8	↓	↓	-	-	-	134	-	0	-	-	Bank SB	
9	↓	↓	-	-	-	71	-	-	0	-	Bank SC	
10	↓	↓	-	-	-	71	-	-	-	0	Bank SD	
11	↓	↓	-	-	-	-	-	-	-	-	ARO	
12	↓	↓	0	-	-	-	-	-	-	-	Bank A	
13	↓	↓	-	0	-	-	-	-	-	-	Bank B	
14	↓	↓	-	-	0	-	-	-	-	-	Bank C	
15	↓	↓	-	-	-	0	-	-	-	-	Bank D	Rod Worths
16	↓	↓	-	-	-	-	0	-	-	-	Bank SA	
17	↓	↓	-	-	-	-	-	0	-	-	Bank SB	
18	↓	↓	-	-	-	-	-	-	0	-	Bank SC	
19	↓	↓	-	-	-	-	-	-	-	0	Bank SD	
20	1291	560	-	-	-	-	-	-	-	-	Low temp	ITC
21	↓	570	-	-	-	-	-	-	-	-	High temp	
22	1230	565	-	-	-	0	-	-	-	-	D @ 0%	
23	↓	↓	-	-	-	23	-	-	-	-	D @ 10%	
24	↓	↓	-	-	-	46	-	-	-	-	D @ 20%	
25	↓	↓	-	-	-	69	-	-	-	-	D @ 30%	
26	↓	↓	-	-	-	92	-	-	-	-	D @ 40%	
27	↓	↓	-	-	-	115	-	-	-	-	D @ 50%	Bank D Integral Worth
28	↓	↓	-	-	-	138	-	-	-	-	D @ 60%	
29	↓	↓	-	-	-	161	-	-	-	-	D @ 70%	
30	↓	↓	-	-	-	184	-	-	-	-	D @ 80%	
31	↓	↓	-	-	-	207	-	-	-	-	D @ 90%	
32	↓	↓	-	-	-	-	-	-	-	-	D @ 100%	

*Fully withdrawn banks (230 steps) are indicated with a dash (-)

- WBN1 used rod swap for the RCCA bank worths. This methodology required the use of 'shadow factors' for inferring the measured bank worths. For the purposes of this benchmark specification, the measured values reported are inferred from shadow factors calculated by CE KENO-VI (Reference 16).
- WBN1 used 4 °F temperature perturbations for the ITC measurements, but 5K values are used here for consistency with available CE data (Reference 1).
- The Bank D integral worth was measured by WBN1 using dilution. The boron concentration chosen for the calculation (1230 ppm) is the average of the ARO and dilution endpoint critical values, corrected to 19.9 at% B-10 (Reference 1).
- Explicit cases for the calculated DBW are not needed. The value can be calculated from the existing cases.

MATERIAL PROPERTIES

All material properties are listed in Section 2.

CAPABILITIES

Successful completion of this benchmark problem can be used to demonstrate the following capabilities:

- Support explicit baffle geometry and radial vacuum boundary condition
- Support quarter core rotational symmetry about core axes
- Definition of instrument tube thimble and full core placement with feedback on neutronics
- Demonstrate problem size, runtime, and required resources on HPC
- Provide capability to define multiple RCCA banks/locations and position banks independently
- Provide automatic optimized domain and energy decomposition for parallelization
- Validate reactivity, rod worths, and temperature coefficients against measured data
- Validate physics parameters and pin powers verses Monte Carlo methods

REFERENCE SOLUTION

The reference values for this benchmark problem are calculated by the SCALE 6.2 Beta (Ref. 6) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The CSAS6 sequence for KENO-VI uses input that includes materials, densities, fuel isotopics, an exact geometry description, and other code options. For this problem, KENO-VI can provide an approximate eigenvalue solution within a small range of uncertainty using the precise geometry specification. It can also perform fission rate tallies for each fuel rod at each prescribed axial location, which can be normalized and post-processed to produce the pin power distribution as well as a distribution of uncertainties.

Due to problem size and detail, including semi-explicit spacer grids and the need for unique units for each power region, a FORTRAN computer code was created to create the input automatically based on a series of simple problem descriptors. This input is too large to include in this document (~10,000,000 lines). This code is located at **/home/agm/git/kenogen**.

CE KENO-VI does not currently have the scalability to run enough particle histories to reduce the fission rate uncertainties to acceptable levels for all cases. A single case, the initial criticality, was used to obtain a 100e9 particle solution for power distribution. The remaining cases were substantially smaller and only the core reactivity is utilized for these. For the single large case, the incore instrumentation tubes were not included to permit octant collapse of the calculated power distribution.

Cross Sections

The reference solution is based on ENDF/B-VII.0 CE cross sections as obtained from SCALE 6.2 (**ce-v7-endf**) (Ref. 6). Only 565K cross sections are utilized. For the isotope H-1, the S(α,β) scattering data is not interpolated internally and is only available at 550K and 600K. Therefore a secondary calculation was performed and the final results include a manually calculated correction factor (-44 pcm).

Materials

The SCALE 6.2 material processor MIPLIB allows common input of compositions across most SCALE codes and sequences. For this problem, the materials are input nearly exactly as described in this specification, with the following exceptions:

- The fuel isotopes are calculated based on the equations in Table 17 (and Ref. 5) and are provided here.

Table P5-3: Problem 5 Calculated Fuel Isotopic Input vs. Enrichment

Isotope	Region 1 Wt%	Region 2 Wt%	Region 3 Wt%
U-234	0.0174%	0.0219%	0.0263%
U-235	2.11%	2.619%	3.10%
U-236	0.0097%	0.0120%	0.0143%
U-238	97.8629%	97.3471%	96.8594%

*Note that explicit O-16 is not needed in MIPLIB input

- For the reference calculation, the pellet-clad gap is modeled explicitly as Helium with nominal density. This could also be modeled as 'void' or air.
- The boron concentration is input by use of weight fractions with the H_2O and boron MIPLIB compositions. For instance, for 1285 ppm, the corresponding weight fraction is 0.001285, and the water fraction is 0.998715. Other concentrations are calculated similarly.
- The material content for the top and bottom nozzles and top and bottom core plates was homogenized manually based on the material densities and heights. These materials are provided in the mixing table below, and are dependent on the soluble boron of the case.
- The neutron pads are assumed to be at the same axial location and height of the active fuel.

Parameters

Two sizes of cases were executed. A single large 100e9 particle history job was executed for the initial criticality case to provide a reference solution for power distribution. For the remaining cases, only 7.5e9 particles were used and these results are only used for eigenvalue references. The detailed specifications and runtimes for these jobs are provided in Table P5-5.

Due to the extremely large problem size, the new parameters **uum=no** and **m2u=no** were utilized for these cases to reduce the memory requirements.

For the cases used only for eigenvalue, a reduced number of axial meshes was used for the fission rate tallies. This improved the run time and memory usage for the case, but results in the output power distribution being incomparable to other cases.

Geometry

The geometry is modeled as explicitly as possible as described in Sections 1.1 to 1.13. A detailed descripton is provided below.

- Explicit representation of the fuel rod stack, plenum, and end plugs. The end plug geometry is a simplified cylinder, and is similar for each of the fuel, poison, and control rods. The plenum spring itself is not modeled.

- Semi-explicit representation of all spacer grids, by dividing the grid mass equally amongst the 289 lattice cells in each assembly, and placing that mass in an equivalent volume box on the outside of each cell at the proper axial location. The spacer grid spacer sleeves are ignored, which are less than 10% of the total grid mass.

- Guide tubes and instrument tubes are assumed to extend from the bottom nozzle to the top nozzle, and the lower dashpot region of the guide tubes is ignored.

- Homogenization of the top and bottom nozzles of each assembly.

- Explicit modeling of Pyrex and RCCA rodlets, axial locations, end plugs, and plenum regions below the top nozzle (ignoring springs). RCCA geometry in and above the top nozzle is ignored. Fully withdrawn RCCAs are also included in the model up to the upper nozzle.

- Explicit inclusion of thimble plugs in upper regions of empty guide tubes which do not contain RCCA or Pyrex rodlets.

- Non-symmetric inclusion of incore instrumentation thimbles. Though this invalidates the quarter symmetry, the effect is expected to be small and inclusion somewhat accounts for the correct effect on the core average reactivity due to displaced moderation.

- Exclusion of primary and secondary source rods.

- Explicit treatment of the core baffle, assuming solid stainless steel.

- Homogenization of upper and lower core plates assuming 50% coolant volume fraction.

- Inclusion of core support structure and containers such as the neutron pads, core barrel, vessel liner, and the carbon steel vessel itself.

- 50 cm axial buffer of moderator between the core plates and axial vacuum (non-reentrant) boundary to assure proper calculation of the core axial leakage.

- The KENO-VI preprocessor permits input and positioning of each of the eight RCCA banks, used for the bank reactivity worth calculations performed in this report.

- All dimensions are cold and do not include thermal expansion.

- For Banks SC and SD, a correction factor is applied to the KENO-VI results (Reference 16) to account for the lack of rotational symmetry. A full core case was not attempted due to the model size. This factor is -53 pcm when Bank D is inserted and -39 pcm when it is withdrawn.

Figure P5-2 provides radial and axial views of the Problem 5 quarter core geometry. The case for initial criticality with Bank D @ 167 steps withdrawn is shown.
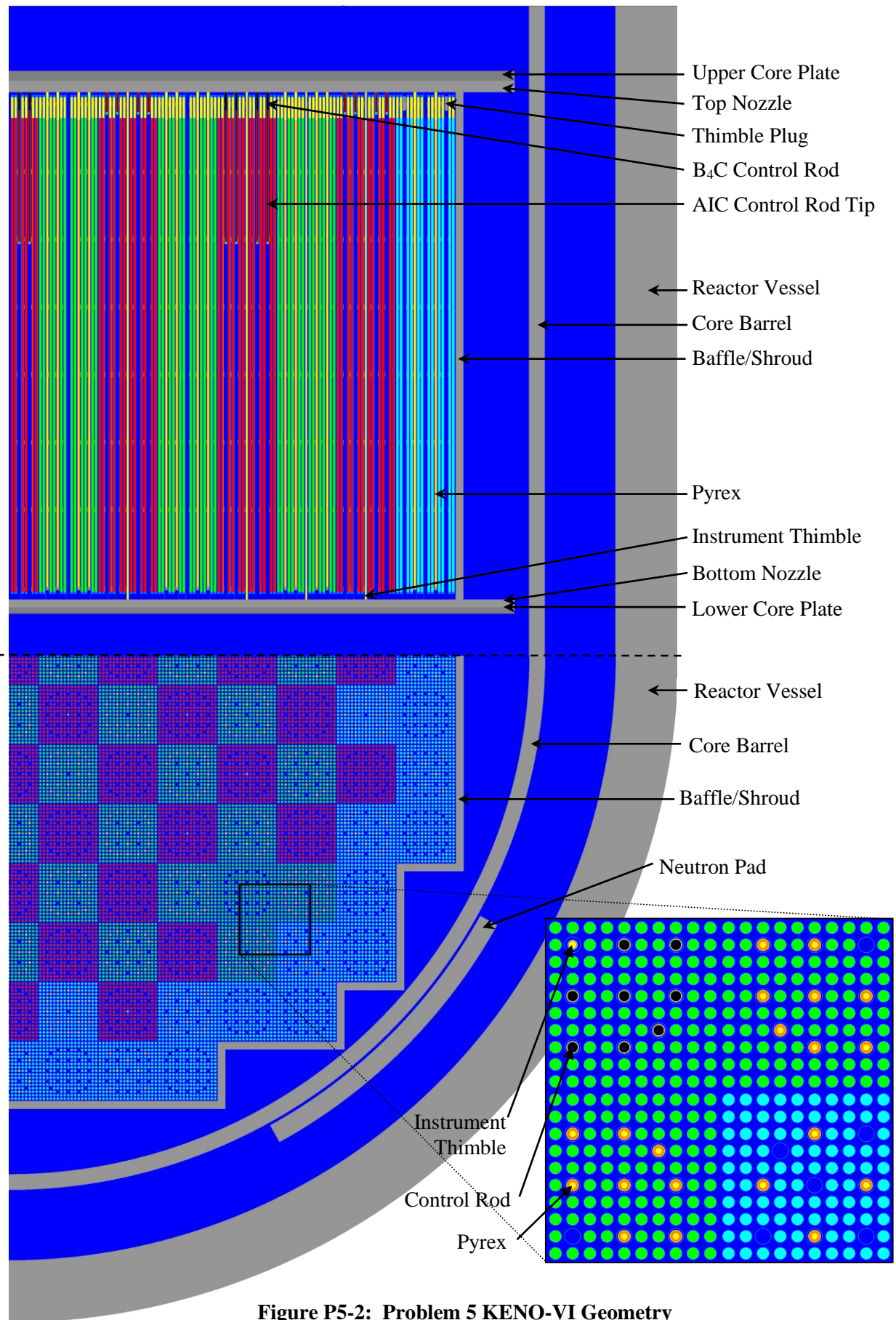
Figure P5-2: Problem 5 KENO-VI Geometry

The figure is labeled with the following callouts:
- Upper Core Plate
- Top Nozzle
- Thimble Plug
- B_4C Control Rod
- AIC Control Rod Tip
- Reactor Vessel
- Core Barrel
- Baffle/Shroud
- Pyrex
- Instrument Thimble
- Bottom Nozzle
- Lower Core Plate
- Reactor Vessel
- Core Barrel
- Baffle/Shroud
- Neutron Pad
- Instrument Thimble
- Control Rod
- Pyrex

Input File

The input for this problem is nearly 10,000,000 lines long, so it is excluded from this document. The files for these problems are currently located on cpile2.ornl.gov at **/home/agm/vera.**

Computer Code

The reference calculations were executed with SCALE 6.2 Beta 2 on the Fission supercomputer at Idaho National Laboratory. The approximate run time for the power distribution case was 29 days on 180 cores, utilizing up to 11 GB of memory per core. The eigenvalue only cases took approximately 45 hours each, also on 240 cores and up to 4 GB of memory per core. See Table P5-5 for more information.

Mixing Table

The following table provides the precise isotopic number densities used for each mixture in the reference problems.

Table P5-4: Reference Mixing Table

Material	Isotope ID	Atom Density (/barn-cm)
2.11% Fuel	8016	4.57591E-02
	92234	4.04814E-06
	92235	4.88801E-04
	92236	2.23756E-06
	92238	2.23844E-02
2.619% Fuel	8016	4.57617E-02
	92234	5.09503E-06
	92235	6.06733E-04
	92236	2.76809E-06
	92238	2.22663E-02
3.1% Fuel	8016	4.57642E-02
	92234	6.11864E-06
	92235	7.18132E-04
	92236	3.29861E-06
	92238	2.21546E-02
Gap	2004	2.68714E-05
Cladding & Zircaloy Grids	24050	3.30121E-06
	24052	6.36606E-05
	24053	7.21860E-06
	24054	1.79686E-06
	26054	8.68307E-06
	26056	1.36306E-04
	26057	3.14789E-06
	26058	4.18926E-07
	40090	2.18865E-02
	40091	4.77292E-03
	40092	7.29551E-03
	40094	7.39335E-03
	40096	1.19110E-03
	50112	4.68066E-06
	50114	3.18478E-06
	50115	1.64064E-06
	50116	7.01616E-05
	50117	3.70592E-05
	50118	1.16872E-04
	50119	4.14504E-05
	50120	1.57212E-04
	50122	2.23417E-05
	50124	2.79392E-05
	72174	3.54138E-09
	72176	1.16423E-07
	72177	4.11686E-07
	72178	6.03806E-07
	72179	3.01460E-07
	72180	7.76449E-07
Inconel	14028	4.04885E-03
	14029	2.05685E-04
	14030	1.35748E-04
	22046	2.12518E-04
	22047	1.91652E-04
	22048	1.89901E-03
	22049	1.39360E-04
	22050	1.33435E-04
	24050	6.18222E-04
	24052	1.19218E-02
	24053	1.35184E-03
	24054	3.36501E-04
	26054	3.61353E-04
	26056	5.67247E-03
	26057	1.31002E-04
	26058	1.74340E-05
	28058	4.17608E-02
	28060	1.60862E-02
	28061	6.99255E-04
	28062	2.22953E-03
	28064	5.67796E-04
Pyrex	5010	9.61468E-04
	5011	3.89444E-03
	8016	4.66888E-02
	14028	1.81641E-02
	14029	9.22749E-04
	14030	6.08994E-04
SS304	6000	3.20895E-04
	14028	1.58197E-03
	14029	8.03653E-05
	14030	5.30394E-05
	15031	6.99938E-05
	24050	7.64915E-04
	24052	1.47506E-02

	Isotope ID	Value		AIC	Isotope ID	Value
	24053	1.67260E-03		**AIC**	47107	2.36159E-02
	24054	4.16346E-04			47109	2.19403E-02
	25055	1.75387E-03			48106	3.41523E-05
	26054	3.44776E-03			48108	2.43165E-05
	26056	5.41225E-02			48110	3.41250E-04
	26057	1.24992E-03			48111	3.49720E-04
	26058	1.66342E-04			48112	6.59276E-04
	28058	5.30854E-03			48113	3.33873E-04
	28060	2.04484E-03			48114	7.84957E-04
	28061	8.88879E-05			48116	2.04641E-04
	28062	2.83413E-04			49113	3.44262E-04
	28064	7.21770E-05			49115	7.68050E-03
B4C	5010	1.52689E-02		**Carbon Steel**	6000	3.93598E-03
	5011	6.14591E-02			26054	4.89841E-03
	6000	1.91820E-02			26056	7.68945E-02
					26057	1.77583E-03
					26058	2.36330E-04

| Isotope ID | Moderator (565K and 0.743 g/cc) | | | |
	1285 ppm	1291 ppm	1170 ppm	1230 ppm
1001	4.96231E-02	4.96228E-02	4.96288E-02	4.96258E-02
5010	1.05835E-05	1.06329E-05	9.63633E-06	1.01305E-05
5011	4.25999E-05	4.27988E-05	3.87874E-05	4.07765E-05
8016	2.48116E-02	2.48114E-02	2.48144E-02	2.48129E-02

| Isotope ID | Top Nozzle (565K and 0.743 g/cc) | | | |
	1285 ppm	1291 ppm	1170 ppm	1230 ppm
1001	4.01217E-02	4.01214E-02	4.01264E-02	4.01240E-02
5010	8.55766E-06	8.60494E-06	7.80118E-06	8.17942E-06
5011	3.44456E-05	3.46360E-05	3.14007E-05	3.29232E-05
6000	6.14459E-05	6.14459E-05	6.14458E-05	6.14459E-05
8016	2.00608E-02	2.00607E-02	2.00632E-02	2.00620E-02
14028	3.02920E-04			
14029	1.53886E-05			
14030	1.01561E-05			
15031	1.34026E-05			
24050	1.46468E-04			
24052	2.82449E-03			
24053	3.20275E-04			
24054	7.97232E-05			
25055	3.35836E-04			
26054	6.60188E-04			
26056	1.03635E-02			
26057	2.39339E-04			
26058	3.18517E-05			
28058	1.01650E-03			
28060	3.91552E-04			
28061	1.70205E-05			
28062	5.42688E-05			
28064	1.38207E-05			

| Isotope ID | Bottom Nozzle (565K and 0.743 g/cc) | | | |
	1285 ppm	1291 ppm	1170 ppm	1230 ppm
1001	3.57666E-02	3.57662E-02	3.57707E-02	3.57685E-02
5010	7.61305E-06	7.67444E-06	6.93770E-06	7.30607E-06
5011	3.06435E-05	3.08906E-05	2.79251E-05	2.94078E-05
6000	8.96008E-05	8.96008E-05	8.96008E-05	8.96008E-05
8016	1.78833E-02	1.78831E-02	1.78853E-02	1.78842E-02
14028	4.41720E-04			
14029	2.24397E-05			
14030	1.48097E-05			
15031	1.95438E-05			
24050	2.13581E-04			
24052	4.11869E-03			
24053	4.67027E-04			
24054	1.16253E-04			
25055	4.89719E-04			
26054	9.62690E-04			
26056	1.51122E-02			
26057	3.49006E-04			
26058	4.64463E-05			
28058	1.48226E-03			
28060	5.70964E-04			
28061	2.48194E-05			
28062	7.91351E-05			
28064	2.01534E-05			

| Isotope ID | Core Plates (565K and 0.743 g/cc) | | | |
	1285 ppm	1291 ppm	1170 ppm	1230 ppm
1001	2.48115E-02	2.48115E-02	2.48145E-02	2.48130E-02
5010	5.28195E-06	5.33040E-06	4.79736E-06	5.08811E-06
5011	2.12605E-05	2.14555E-05	1.93100E-05	2.04803E-05
6000	1.60447E-04	1.60447E-04	1.60447E-04	1.60447E-04
8016	1.24058E-02	1.24058E-02	1.24072E-02	1.24065E-02
14028	7.90985E-04			
14029	4.01826E-05			
14030	2.65197E-05			
15031	3.49969E-05			
24050	3.82458E-04			
24052	7.37532E-03			
24053	8.36302E-04			
24054	2.08173E-04			
25055	8.76936E-04			
26054	1.72388E-03			
26056	2.70613E-02			
26057	6.24963E-04			
26058	8.31710E-05			
28058	2.65427E-03			
28060	1.02242E-03			
28061	4.44439E-05			
28062	1.41707E-04			
28064	3.60885E-05			

REFERENCE SOLUTION RESULTS AND MEASURED DATA

The eigenvalues calculated by CE KENO-VI for the reference cases are provided below in Table P5-6. For the ten critical configurations, WBN1 is assumed to be critical. The reference ZPPT solutions are calculated based on the data from WBN1 and provided in Reference 16.

1. Core initial criticality was achieved by positioning of the main regulating control rod bank, Bank D, at a position of 167 steps withdrawn and a boron concentration of 1285 ppm.
   .
2. Nine other critical configurations are modeled, including the all-rods-out (ARO) condition, and each bank insertion during rod worth testing. For all banks other than Bank D (the reference bank), the measured Bank is fully inserted and Bank D is partially inserted at the measured critical position. For the inserted bank cases, the dilution endpoint boron concentration of 1170 ppm is used.

3. The control Bank D worth was measured via soluble boron dilution. The reference worth is calculated by Bank D insertion at the dilution endpoint boron concentration of 1170 ppmB. Sensitivity studies indicate that the selection of the boron concentration (ARO, endpoint, or average) is a secondary effect on the bank worth, producing only a 2 pcm effect.

4. The remaining control bank reactivity worths were measured via rod swap against Bank D at the boron dilution endpoint of 1170 ppm. The 'predicted' bank worths are calculated with the reference bank fully withdrawn, and compared to 'inferred' measurements using precalculated rod shadow factors. These factors have been recalculated with CE KENO-VI and are built into the provided measured worths below. This methodology is consistent with that used for WBN1C1.

5. The Differential Boron Worth (DBW) is calculated at ARO conditions using the ARO critical boron concentration (1291 ppm) and the dilution endpoint concentration (1170 ppm). Sensitivity studies indicate that the selection of the Bank D position is a secondary effect on the DBW, producing only a 0.02 pcm/ppm effect.

6. The Isothermal Temperature Coefficient (ITC) is calculated over the range of 560K to 570K at ARO conditions. Due to limitations in CE KENO-VI, the value is calculated with a more complicated methodology described in Appendix G.

7. The integral RCCA worth curve is calculated using Bank D insertion increments of 10% (23 steps) at 565K and the average of the ARO critical boron concentration and the dilution endpoint concentration, adjusting to 19.9 at% B-10. All other banks are withdrawn for these calculations.

The measured data for the WBN1 Cycle ZPPT has been previously provided to CASL from TVA and approved for public release in Reference 16.

Table P5-5: Problem 5 Monte Carlo Statistics

	Power Distribution	Eigenvalues
Total # Particles	100e9	7.5e9
# Particles / Generation	10e6	5e6
# Generations	10,000	1,500
# Skipped Generations	500	500
# Cores	180	300
Memory / Core	10.7 GB	4 GB
Runtime	29 days	44 hours
Eigenvalue Uncertainty	± 0.25 pcm	< ± 1.2 pcm
Average Pin Power Uncertainty	± 0.209%	n/a
Maximum Pin Power Uncertainty (by Power)	Power < 1.0: ± 1.630% Power > 1.0: ± 0.414%	n/a

Table P5-6: Problem 5 Reference Solution Eigenvalue Results

Case	Boron (ppm)	Temp (K)	A	B	C	D	SA	SB	SC	SD	k-effective	
						Bank Position (steps withdrawn)						
1	1285	565	-	-	-	167	-	-	-	-	0.999899 ± 0.000010	Criticals
2	1291	↓	-	-	-	-	-	-	-	-	1.000321 ± 0.000013	
3	1170	↓	0	-	-	97	-	-	-	-	0.998797 ± 0.000010	
4	↓	↓	-	0	-	113	-	-	-	-	0.999358 ± 0.000013	
5	↓	↓	-	-	0	119	-	-	-	-	0.999039 ± 0.000013	
6	↓	↓	-	-	-	18	-	-	-	-	0.999084 ± 0.000013	
7	↓	↓	-	-	-	69	0	-	-	-	0.999022 ± 0.000012	
8	↓	↓	-	-	-	134	-	0	-	-	0.999324 ± 0.000012	
9	↓	↓	-	-	-	71	-	-	0	-	0.998983 ± 0.000013	
10	↓	↓	-	-	-	71	-	-	-	0	0.998976 ± 0.000013	
11	↓	↓	-	-	-	-	-	-	-	-	1.012841 ± 0.000013	Rod Worths
12	↓	↓	0	-	-	-	-	-	-	-	1.003716 ± 0.000014	
13	↓	↓	-	0	-	-	-	-	-	-	1.003941 ± 0.000012	
14	↓	↓	-	-	0	-	-	-	-	-	1.002843 ± 0.000013	
15	↓	↓	-	-	-	0	-	-	-	-	0.998815 ± 0.000013	
16	↓	↓	-	-	-	-	0	-	-	-	1.008281 ± 0.000013	
17	↓	↓	-	-	-	-	-	0	-	-	1.002018 ± 0.000013	
18	↓	↓	-	-	-	-	-	-	0	-	1.007749 ± 0.000012	
19	↓	↓	-	-	-	-	-	-	-	0	1.007745 ± 0.000013	
20	1291	560	-	-	-	-	-	-	-	-	1.000608 ± 0.000014	ITC
21	↓	570	-	-	-	-	-	-	-	-	1.000034 ± 0.000014	
22	1230	565	-	-	-	0	-	-	-	-	0.992755 ± 0.000013	Bank D Integral Worth Curve
23	↓	↓	-	-	-	23	-	-	-	-	0.993162 ± 0.000013	
24	↓	↓	-	-	-	46	-	-	-	-	0.994555 ± 0.000013	
25	↓	↓	-	-	-	69	-	-	-	-	0.997369 ± 0.000015	
26	↓	↓	-	-	-	92	-	-	-	-	1.000279 ± 0.000012	
27	↓	↓	-	-	-	115	-	-	-	-	1.002542 ± 0.000013	
28	↓	↓	-	-	-	138	-	-	-	-	1.004163 ± 0.000013	
29	↓	↓	-	-	-	161	-	-	-	-	1.005300 ± 0.000014	
30	↓	↓	-	-	-	184	-	-	-	-	1.006073 ± 0.000013	
31	↓	↓	-	-	-	207	-	-	-	-	1.006468 ± 0.000012	
32	↓	↓	-	-	-	-	-	-	-	-	1.006584 ± 0.000013	

- Eigenvalues are corrected for KENO-VI S(α,β) limitation (~-43 pcm).
- All results are for cold dimensions. The approximate worth of thermal expansion for WBN1 based on nodal methods is -57 pcm (Reference 16). This correction is NOT included here.
- The ITC results are derived from the rigorous KENO-VI calculations presented in Appendix G.
- The KENO-VI results for Bank SC and SD insertions include a correction factor for not using rotational symmetry in the eigenvalue calculation (up to -53 pcm – Reference 16).
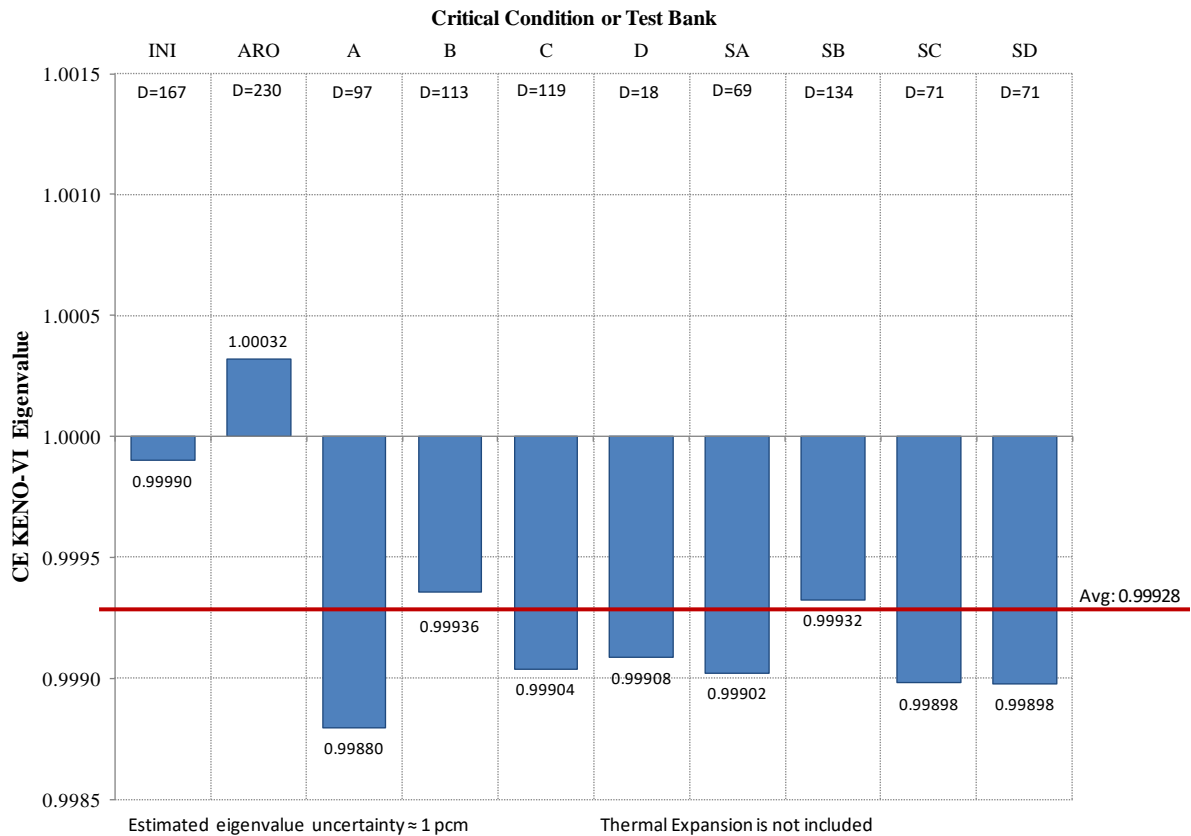
Figure P5-3: Problem 5 Reference Solution Criticals

The ZPPT control bank worths, differential boron worth, and isothermal temperature coefficient were calculated and provided in the table below using the following equation for reactivity difference:

$$\rho = \left(1/k_1 - 1/k_2\right) \times 10^5 \ [pcm]$$

Table P5-7: Problem 5 Measured and Reference Solution ZPPT Results

Test Result	Measured	CE KENO-VI	Difference
Initial Criticality[†]	1.00000[‡]	0.999899 ± 0.000010	-10 ± 1 pcm
Bank A Worth (pcm)	843	898 ± 2	6.4% ± 0.2%
Bank B Worth	879	875 ± 2	-0.5% ± 0.2%
Bank C Worth	951	984 ± 2	3.5% ± 0.2%
Bank D Worth	1342	1386 ± 2	3.3% ± 0.1%
Bank SA Worth	435	447 ± 2	2.6% ± 0.4%
Bank SB Worth	1056	1066 ± 2	1.0% ± 0.2%
Bank SC Worth	480	499 ± 2	3.9% ± 0.4%
Bank SD Worth	480	499 ± 2	4.0% ± 0.4%
Total Bank Worths	6467	6654 ± 4	2.9% ± 0.1%
DBW (pcm/ppm)	-10.77	-10.21 ± 0.02	0.56
ITC (pcm/F)	-2.17	-3.18 ± 0.04	-1.01

[†]Critical conditions are 1285 ppm and Bank D at 167 steps withdrawn

[‡]The initial criticality result does not account for thermal expansion (approx. -57 pcm)
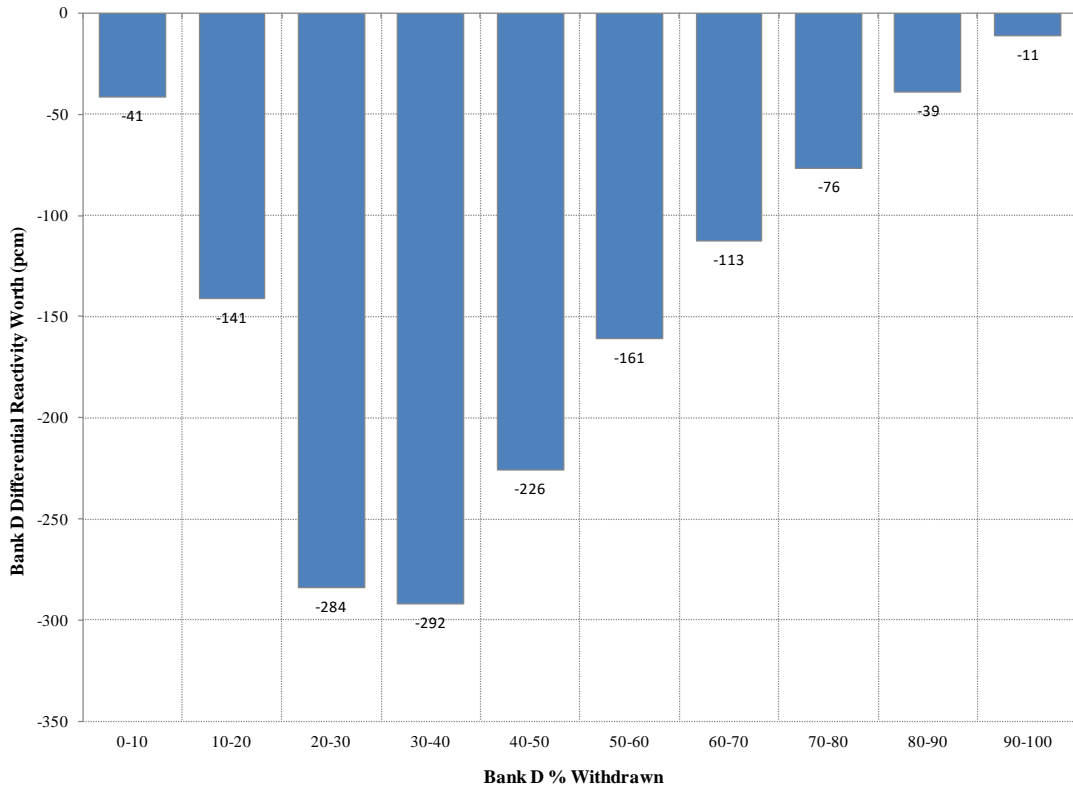
Figure P5-4: Problem 5 CE KENO-VI Bank D Differential Worths
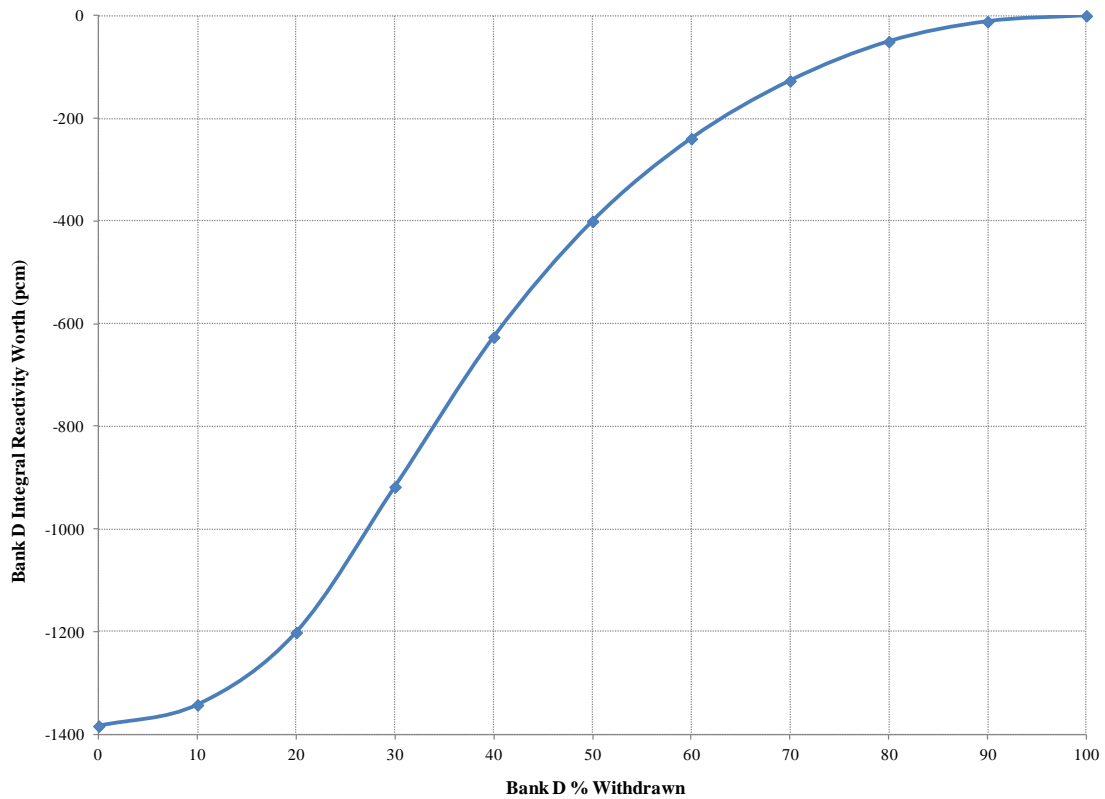
Figure P5-5: Problem 5 CE KENO-VI Bank D Integral Worth Curve

The individual pin powers are too large to include in this document. They can be obtained by request from the author at godfreyat@ornl.gov . Summary results for the radial and axial power shapes for the single 100e9 particle case are provided below. More numerical results are provided in Appendix F. Note that unlike the previous results, this case did not include the incore instrument thimbles in order to maintain octant symmetry and produce lower power distribution uncertainties. The eigenvalue for this case is **1.000072 ± 0.000002.**

	H	G	F	E	D	C
8	0.9487					
9	0.9193	0.9973				
10	1.0181	0.9083	1.0648			
11	0.9850	1.0819	1.0412	1.1615		
12	1.0647	1.0471	1.1746	1.0850	1.2368	
13	1.0480	1.1619	1.1520	1.1508	0.8969	0.9126
14	1.0841	1.0652	1.1039	1.0496	0.9452	0.6296
15	0.7931	0.9071	0.8046	0.6590		

Max: 1.2368   **Avg:**   1.0000

	H	G	F	E	D	C
8	0.004%					
9	0.003%	0.002%				
10	0.003%	0.002%	0.002%			
11	0.003%	0.002%	0.002%	0.002%		
12	0.003%	0.002%	0.002%	0.002%	0.002%	
13	0.003%	0.002%	0.002%	0.002%	0.002%	0.002%
14	0.003%	0.002%	0.002%	0.002%	0.002%	0.002%
15	0.003%	0.002%	0.002%	0.002%		

Max: 0.004%   **Avg:**   0.002%

Figure P5-6: Problem 5 CE KENO-VI Radial Assembly Powers and Uncertainties
(Octant Symmetry)
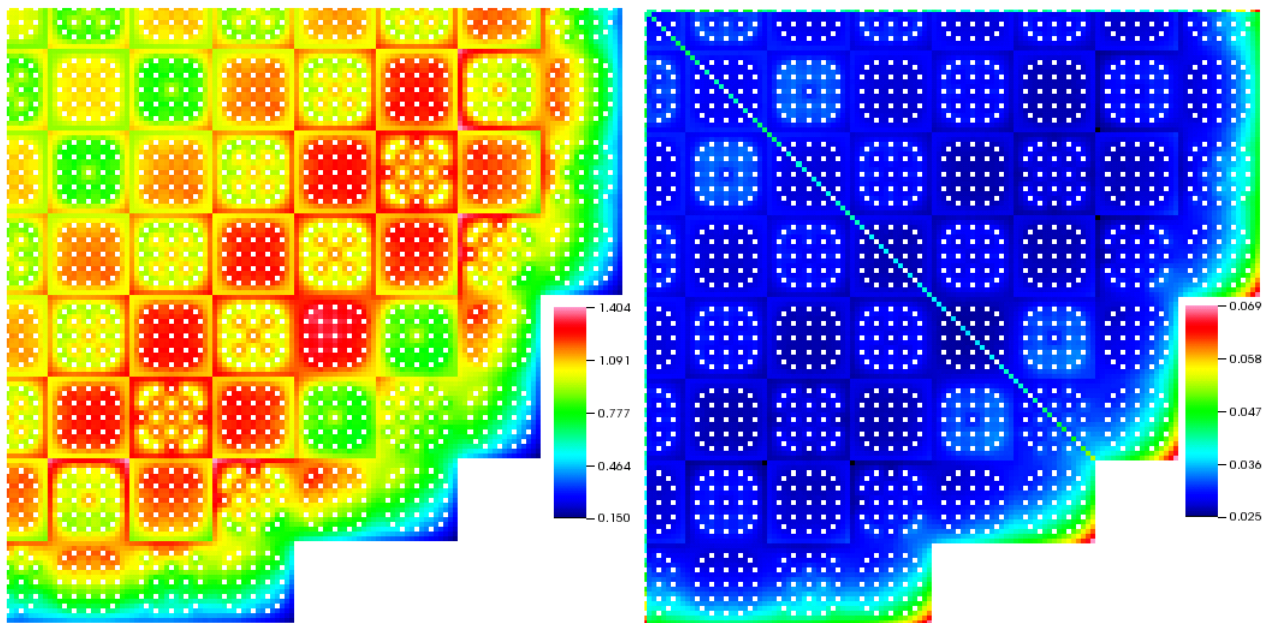
Figure P5-7: Problem 5 CE KENO-VI Radial Power Distribution and Uncertainty (%)
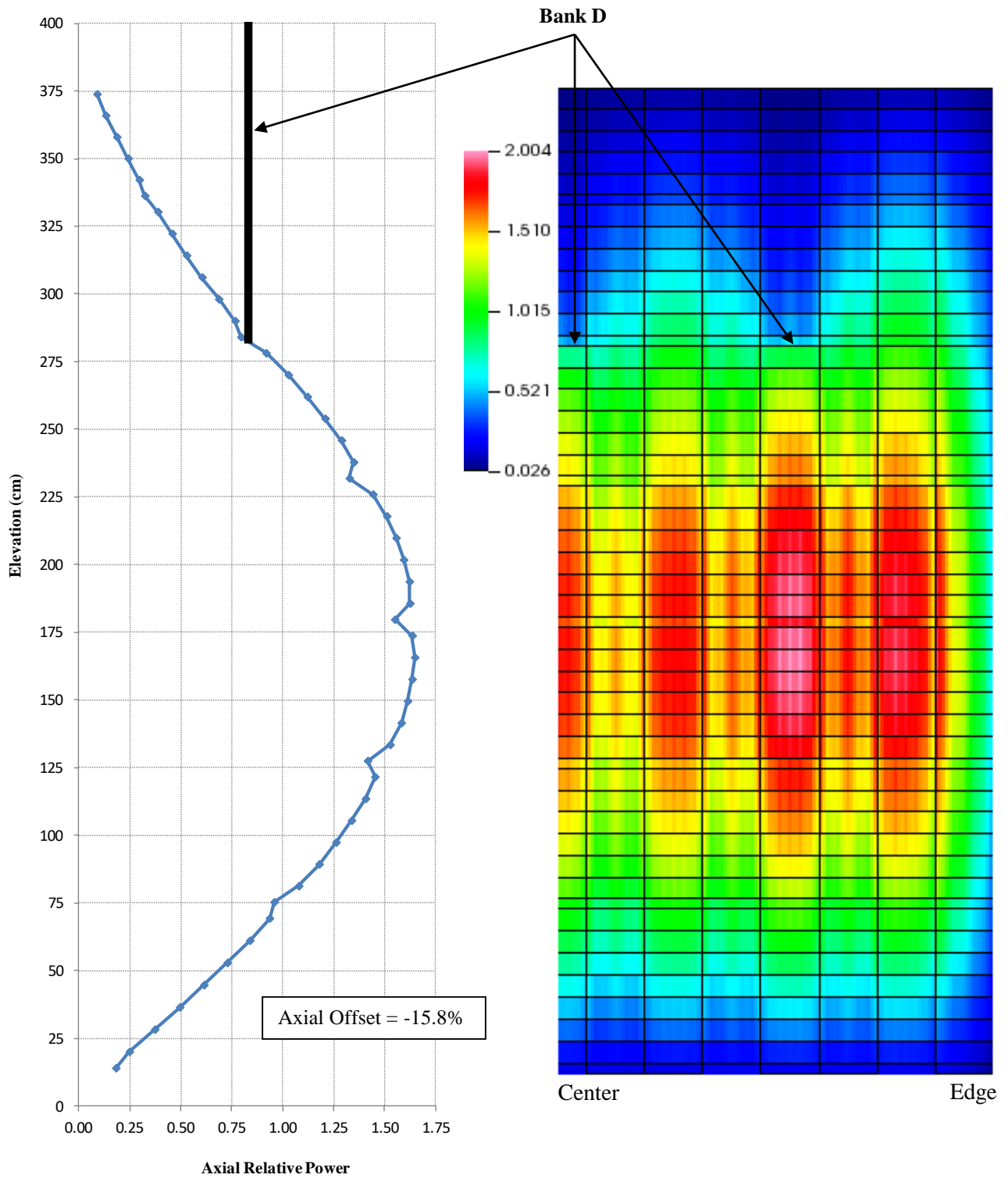
Figure P5-8: Problem 5 CE KENO-VI Average Axial Power Distribution
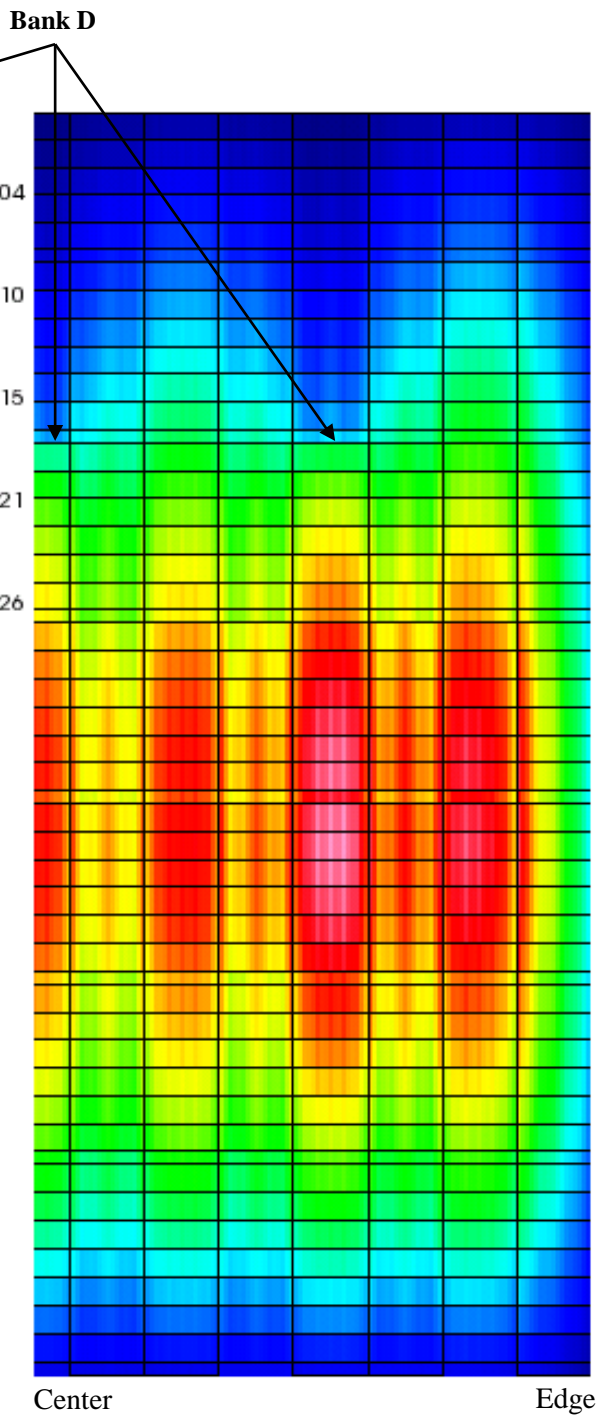
Figure P5-9: Problem 5 CE KENO-VI Axial Slice of 3D Power Distribution
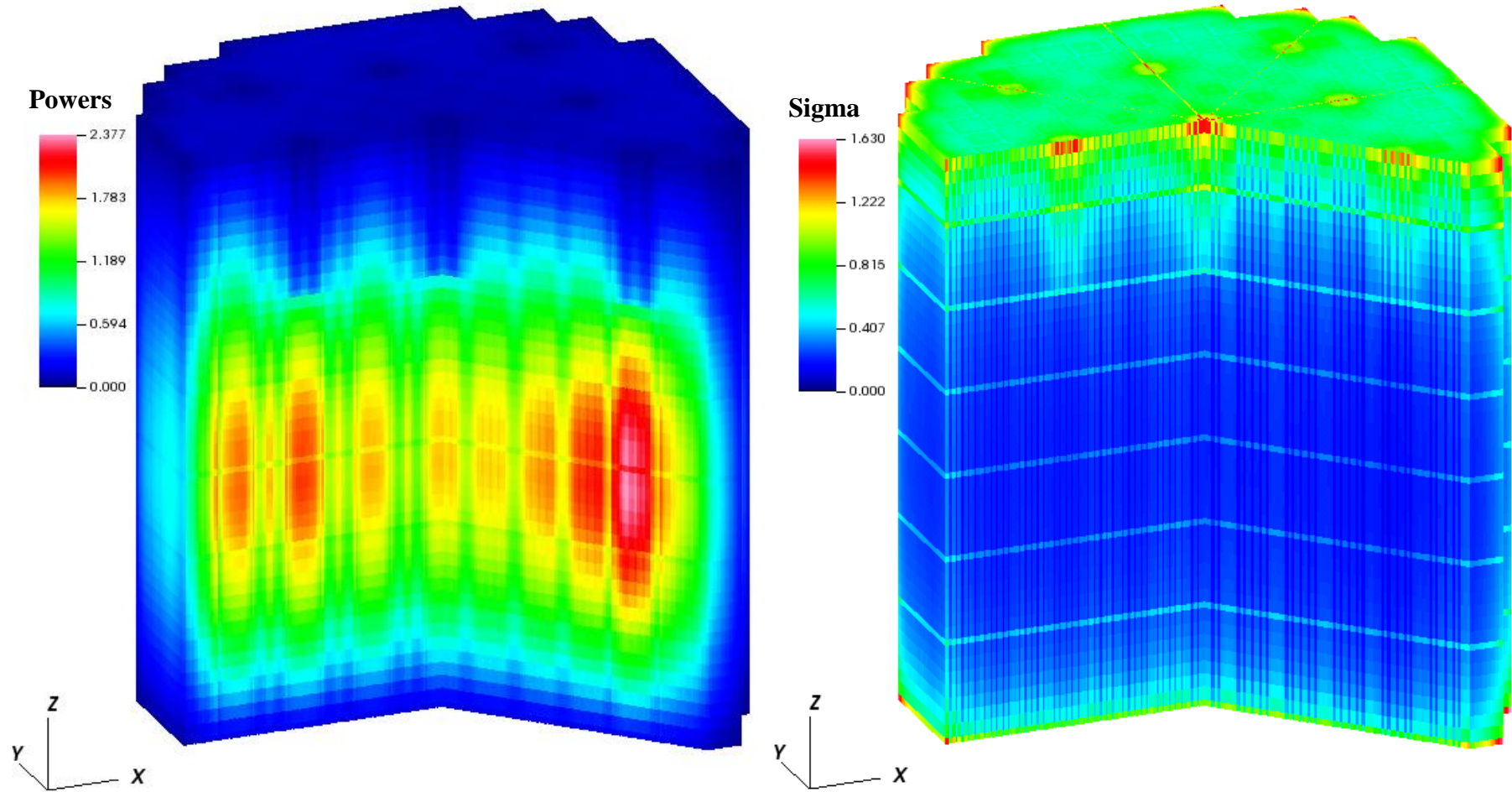
Figure P5-10: Problem 5 CE KENO-VI 3D Fission Rate Distribution and Uncertainties (%)

Problem #6: 3D HFP Assembly

PURPOSE

This core physics benchmark problem is the first to demonstrate VERA's performance for an operating reactor condition requiring a coupled multi-physics iterative solution. The geometry is a single PWR fuel assembly identical to Problem 3. However, this assembly is at typical full power and nominal flow conditions, requiring the additional capability of thermal-hydraulic feedback to the neutronics in both the fuel and coolant properties. Successful completion demonstrates the capability to predict the eigenvalue, pin power distribution, fuel temperatures, and coolant conditions without depletion or fission products.

SPECIFICATIONS

The problem geometry is identical to Problem 3 (3A) and consists of a single Westinghouse 17x17-type fuel assembly at beginning-of-life (BOL) and Hot Full Power (HFP) conditions, based on the WBN1 data provided in Sections 1.1 to 1.4. The materials are standard for this type of reactor: UO_2 fuel, Zircaloy-4 cladding, Inconel-718, Stainless Steel Type 304, and water. The moderator also contains soluble boron as a chemical shim for maintaining criticality. The focus of this problem is to demonstrate the ability to provide the neutronics with thermal-hydraulic feedback and iterate to convergence. There is no transmutation of isotopics (include no xenon).

Table P6-1 provides the problem specifications:

Table P6-1: Problem 6 Input Specification

Input	Value	Section
Fuel Density	10.257 g/cc	2.2
Fuel Enrichment	3.1%	2.1
Inlet Coolant Temperature	565 K	3
Reactor Pressure	2250 psia	3
Boron Concentration	1300 ppm	3
Rated Power (100%)	17.67 MW	3
Rated Coolant Mass Flow (100%)	0.6823 Mlbs/hr	3

- The fuel assembly geometry is identical to Problem 3.
- The inlet moderator temperature is 565K. With T/H feedback the density will be calculated.
- The assembly power is the average assembly power for WBN1 (3411 MW divided by193 fuel assemblies).
- The assembly flow is the total flow (144.7 Mlbs/hr), reduced by 9% to account for bypass flow, and divided by the number of fuel assemblies.

MATERIAL PROPERTIES

All material properties are listed in Section 2. The thermal-hydraulic properties (fuel thermal conductivity, gap conductance, steam properties, etc) are not specified.

CAPABILITIES

Successful completion of this benchmark problem can be used to demonstrate the following capabilities:

- Input based on reactor conditions such as percent and rated power and flow
- Determine sub-cooled moderator density from reactor temperatures and pressure
- Provide pin-by-pin T/H feedback for fluid temperature and density
- Provide pin-by-pin fuel temperature feedback for Doppler absorption
- Perform coupled neutronics-T/H-fuel temperature iteration until convergence within criteria provided by the user.
- Ability to converge multiple coupled physics calculations on parallel processors
- Account for inter-pin fuel temperature distribution on cross-section generation
- Account for axially varying moderator density above fuel stack
- Manage and output pin/channel level density distribution edits
- Manage and output pin or intra-pin level fuel temperature edits
- Output assembly level T/H and fuel temperature edits (1D, 2D, 3D density, temperature)
- Output AFD (axial flux difference)
- Demonstrate convergence characteristics for coupled problem
- Validate single physics components against reliable references at HFP conditions (MC, VIPRE-W)

REFERENCE SOLUTION

No reference solution exists for this problem at this time.

Problem #7: 3D HFP BOC Physical Reactor

PURPOSE

This core physics benchmark problem is the first to demonstrate VERA's performance for an operating reactor in full geometric detail. The geometry is the Watts Bar Cycle 1 core identical to Problem 5. However, the problem is run a full power and nominal flow conditions, utilizing thermal-hydraulic feedback to the neutronics in both the fuel and coolant properties. Additionally this problem adds the requirements for calculation of equilibrium xenon isotopics and critical soluble boron search. Successful completion demonstrates the capability to predict the critical boron, pin power distribution, fuel temperatures, and coolant conditions for the entire core, without depletion.

SPECIFICATIONS

The problem geometry is identical to Problem 5 and consists of a full core of Westinghouse 17x17-type fuel assemblies in the WBN1 initial loading pattern (Sections 1.1 to 1.7 and Section 1.12). The core is at beginning-of-life (BOL) and Hot Full Power (HFP) conditions, including nominal power and flow. The RCCA banks are fully withdrawn, except for Bank D which remains slightly inserted for reactivity control. In order to properly predict a HFP power distribution, the equilibrium concentration of the fission product Xenon must be calculated and distributed correctly in each fuel rod location in the core. Finally, the code must also calculate the soluble boron concentration that keeps the reactor core critical (k-effective = 1.0).

The loading pattern and core geometry are shown in the section on Problem 5, and in Table P5-1. Table P7-1 provides some additional problem specifications:

Table P7-1: Problem 7 Input Specification

Input	Value	Section
Inlet Coolant Temperature	565 K	3
Reactor Pressure	2250 psia	3
Rated Power (100%)	3411 MW	3
Rated Coolant Mass Flow (100%)	131.7 Mlbs/hr	3
RCCA Bank D Position (steps withdrawn)	215	-

- The core geometry is identical to the WBN1 geometry described in Problem 5.
- The inlet moderator temperature is 565K. With T/H feedback the density will be calculated.
- The core flow is the total flow (144.7 Mlbs/hr) reduced by 9% to account for bypass flow (unheated).

MATERIAL PROPERTIES

All material properties are listed in Section 2. The thermal-hydraulic properties (fuel thermal conductivity, gap conductance, steam properties, etc) are not specified.

CAPABILITIES

Successful completion of this benchmark problem can be used to demonstrate the following capabilities:

- Provide reactivity feedback from equilibrium xenon conditions
- Calculate critical soluble boron concentration given target k-effective
- Account for reactor core bypass flow around core and through guide/instrument tubes thimbles
- Account for radial moderator density in baffle region (radial reflector)
- Capable of varying core inlet temperature with core power
- Output critical boron concentration and target k-effective
- Demonstrate full core coupled neutronics-T/H solution at actual HFP conditions

REFERENCE SOLUTION

No reference solution exists for this problem at this time.

Problem #8: Physical Reactor Startup Flux Maps

PURPOSE

This core physics benchmark problem is the next in the progression to provide the opportunity for comparison to measured plant data. The geometry is equivalent to that of Problems 5 and 7. However, rather than executing a single statepoint at BOC HFP equilibrium conditions, the code must provide for time-dependent simulation of a power escalation procedure, and include predictions of the incore instrumentation response at various points during the startup. As with Problem 7, thermal-hydraulic feedback to the neutronics is required. Additional requirements include the calculation of transient xenon isotopics (in the absence of depletion). Successful completion demonstrates the capability to predict the critical boron concentration and measured incore flux distributions that were measured at an operating reactor. Depletion is not necessarily required at this time, though it may be used to explicitly update the transient xenon concentrations.

At this time measured values do not exist for Problem 8. The WBN1C1 initial startup occurred over a very long period of initial tests, which included several planned and unplanned turbine trips and reactor shutdowns. The shear length of this maneuver will make it difficult to model. Additionally, the measured data needed is either difficult to find or simply unavailable. For these reasons, this specification includes only a hypothetical startup procedure and will be revised at a later date when measured data is available and complete.

SPECIFICATIONS

The core geometry and operating characteristics are the same as provided in Problems 5 and 7. Time dependent cases must be input/output to permit modeling of the entire power maneuver. Power is initially zero at BOC, fresh fuel, and no xenon conditions. Power is then increased gradually through a prescribed ramp procedure, stopping occasionally for incore flux maps and other plant procedures at various power plateaus. The xenon distribution at these plateaus is likely NOT at equilibrium conditions, so transient xenon concentrations should be determined for each core location for each time step. For each step, the critical boron concentration should also be calculated for comparison to plant data. The RCCA's are gradually removed as power increases using 128 step overlap.
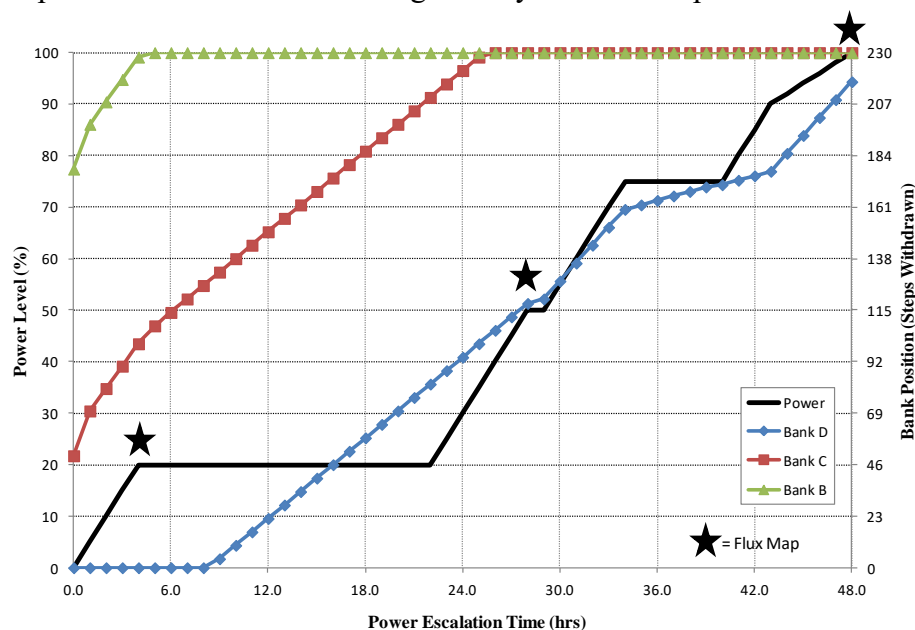
Figure P8-1: Problem 8 Reactor Startup Sequence

Table P8-1: Problem 8 Power Maneuver Specification

Case	Hours	Power	Bank B	Bank C	Bank D	Flux Map
1	0.0	0.0	178	50	0	
2	1.0	5.0	198	70	0	
3	2.0	10.0	208	80	0	
4	3.0	15.0	218	90	0	
5	4.0	20.0	228	100	0	Yes
6	5.0	20.0	230	108	0	
7	6.0	20.0	230	114	0	
8	7.0	20.0	230	120	0	
9	8.0	20.0	230	126	0	
10	9.0	20.0	230	132	4	
11	10.0	20.0	230	138	10	
12	11.0	20.0	230	144	16	
13	12.0	20.0	230	150	22	
14	13.0	20.0	230	156	28	
15	14.0	20.0	230	162	34	
16	15.0	20.0	230	168	40	
17	16.0	20.0	230	174	46	
18	17.0	20.0	230	180	52	
19	18.0	20.0	230	186	58	
20	19.0	20.0	230	192	64	
21	20.0	20.0	230	198	70	
22	21.0	20.0	230	204	76	
23	22.0	20.0	230	210	82	
24	23.0	25.0	230	216	88	
25	24.0	30.0	230	222	94	
26	25.0	35.0	230	228	100	
27	26.0	40.0	230	230	106	
28	27.0	45.0	230	230	112	
29	28.0	50.0	230	230	118	Yes
30	29.0	50.0	230	230	120	
31	30.0	55.0	230	230	128	
32	31.0	60.0	230	230	136	
33	32.0	65.0	230	230	144	
34	33.0	70.0	230	230	152	
35	34.0	75.0	230	230	160	
36	35.0	75.0	230	230	162	
37	36.0	75.0	230	230	164	
38	37.0	75.0	230	230	166	
39	38.0	75.0	230	230	168	
40	39.0	75.0	230	230	170	
41	40.0	75.0	230	230	171	
42	41.0	80.0	230	230	173	
43	42.0	85.0	230	230	175	
44	43.0	90.0	230	230	177	
45	44.0	92.0	230	230	185	
46	45.0	94.0	230	230	193	
47	46.0	96.0	230	230	201	
48	47.0	98.0	230	230	209	
49	48.0	100.0	230	230	215	Yes

MATERIAL PROPERTIES

All material properties are listed in Section 2 and are the same for Problems 5 and 7. The incore detectors are typical fission chambers located at the center of the instrumented thimble locations.

CAPABILITIES

Successful completion of this benchmark problem can be used to demonstrate the following capabilities:

- Provide reactivity feedback from transient xenon conditions
- Allow multiple dependent statepoints based on short term (hourly) time stepping
- Input definition of incore instrument model
- Calculation of instrument cross sections
- Calculation of normalized instrument response for each specified core location
- Demonstrate parallelism and runtimes for realistic number of reactor analysis cases
- Output predicted incore instrument responses
- Validate predicted incore instrument responses against measured plant data

REFERENCE SOLUTION

No reference solution exists for this problem at this time.

Problem #9: Physical Reactor Depletion

PURPOSE

Problem 9 represents one of the most critical capabilities for power reactor simulation, the depletion of the fuel and burnable absorbers. Like the previous problem, time-dependence of the reactor at operating conditions in pseudo-steady state is a major requirement. However, this problem increases the required time scale to the length of a typical 18-month fuel cycle. This requires a significant number of time steps for accurate isotopic depletion and decay, as well as direct core follow simulations for substantial power maneuvers or periods of low power operation. The quality of the comparisons to measured data is partially dependent on how faithfully the actual operating history can be simulated, which can vary depending on the computational requirements of different M&S tools. Successful completion of Problem 9 is demonstrated by successful comparison to measured critical boron concentrations and measured instrument response distributions from WBN1 throughout the entire fuel cycle. Accurate prediction of the fuel cycle length is essential.

When generating these specifications, a typical industry benchmarking approach is applied using average operating conditions. Thermal-hydraulic feedback is required for at-power conditions, and the long time scale requires models for determining fuel temperatures as the fuel rod changes with temperature, irradiation, and burnup. The critical boron search capability is used to compare to the measured soluble boron concentrations when available, and the incore detector response capability provides direct comparison to incore flux map data that is typically produced every 4-6 weeks for standard plant core surveillance activities. Finally, the ability to predict cycle length and the fuel burnup distribution accurately is required before moving forward to Problem 10 through a restart capability.

At this time the following data for WBN1C1 has either not be obtained or cannot be released. This document will be revised when and if the data becomes available.

- Incore flux map data.
- Estimated critical conditions for startups following mid-cycle outages
- Measured boron-10 concentration for the reactor coolant system

SPECIFICATIONS

The WBN1 reactor core geometry and rated operating characteristics are the same as provided in the previous whole reactor problems. For convenience, the relevant parameters and input for this problem are provided in Table P9-1. Steady-state depletion cases are required, beginning at beginning-of-cycle (BOC) and continuing to end-of-cycle (EOC). The results produced from the detailed model from Problem 8 are not required. A restart file is required to be written at EOC to enable subsequent calculations and fuel shuffling, and ideally mid-cycle restarts may be required to precisely model instantaneous measured conditions for critical boron, flux maps, or mid-cycle criticals, if those conditions differ significantly from their average over that time period.

The time step sizes should be small enough to produce accurate depletion of the fuel isotopes, dependent on the method used. Each time step may have different operating parameters, such as reactor power, flow, inlet temperature, and control rod bank positions, averaged over the time step to preserve the historical burnup distribuition and flux spectrum as closely as possible. Explicit modeling of short term transients or shutdown periods is not required, as long as they do not significantly impact the isotopics of subsequent, at-power comparisons.

Because neither Banks SC or SD are used at operating conditions, the cycle depletion may be performed in quarter symmetry.

Table P9-1: Problem 9 Input Specification

Input	Value	Section
Rated Power (100%)	3411 MW	3
Rated Coolant Mass Flow (100%)	131.7 Mlbs/hr	3
Reactor Pressure	2250 psia	3
Cycle Length	441.0 EFPDs	3
EOC Exposure	16.939 GWd/MT	3
RCCA Overlap (steps withdrawn)	128	3

- The core geometry is identical to the WBN1 geometry described in Problem 5.
- The core flow is the total flow (144.7 Mlbs/hr) reduced by 9% to account for bypass flow (unheated). The core flow is assumed to be constant for the entire fuel cycle.
- The reactor pressure in the vessel is assumed to be the constant design value. Variations in pressure throughout the cycle were minimal.
- The cycle length and EOC exposure is calculated based on measured data and the operating history leading up to the Cycle 2 refueling outage, correcting for slight differences in the core fuel loading between the actual fuel as-built information and that provided in this document.

The operating power history for WBN1C1 was provided by TVA in Reference 18. Figure P9-1 displays the power history vs calendar date. Observable is an initial startup extending approximately four months, five mid-cycle shutdowns, one of which lasted approximately 18 days, and an extended power coastdown at EOC for approximately seven weeks.
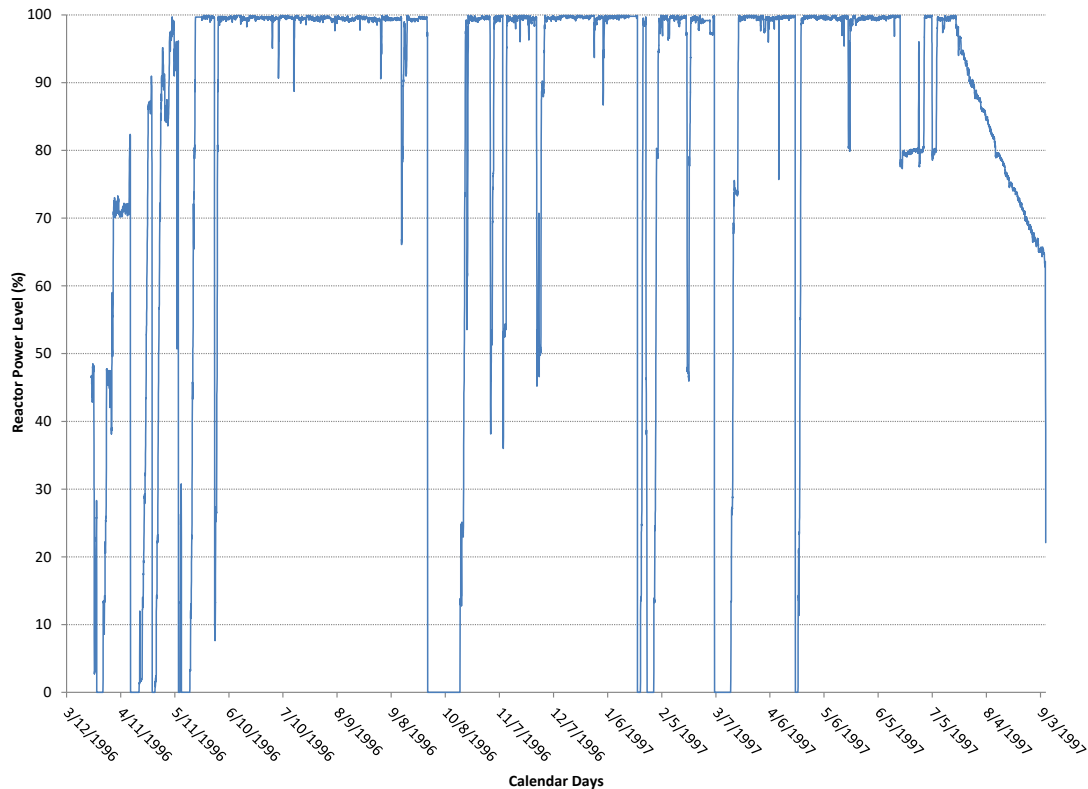
Figure P9-1: Problem 9 Reactor Power History by Date

The depletion model was built from operating data with the following modifications:

1. The initial low power startup sequence was approximated based on a figure in Reference 20, up to approximately 5 EFPDs and 46% power.
2. Any bad or inconsistent data points were removed as necessary.
3. The starting cycle exposure was initialized following the initial low power testing based on the boron measurements provided in Reference 17.
4. The power history was renormalized to preserve the measured cycle exposure (+0.14%)
5. The power history was renormalized to account for slight heavy metal mass loading differences between the as-built assemblies fuel and this specification (+0.2%)
6. Depletion data points were selected at approximately 15 EFPD intervals, preferentially occurring at times when the plant was at equilibrium, when measurements are available, or just prior to a mid-cycle shutdown. The interval was assumed to be about half of industry practice to accommodate codes which will perform 3D depletion on-the-fly (such as in VERA). The total number of depletion points was intentionally minimized to accommodate methods with longer run times.
7. For the startup and shutdown periods, an endpoint-based ramp is provided (i.e. the values are the conditions at the end of the time step. The endpoints were selected to be similar to plant conditions while preserving the average power over the time step.
8. For the main depletion, at or near HFP, the exposure-weighted average of each input parameter was calculated for each interval.

The final model inputs for Problem 9, based on the data from WBN1C1, are presented in Figures P9-2 to P9-4, including relative power level, inlet temperature, and regulating control Bank D position. These figures also include the original operating data for reference. Note that the "stair step" curve for the model indicates average values over the depletion interval, while the sloped lines indicate exact data given for the depletion endpoints.

Note that with control banks operated in overlap, control Banks C, B, and A move sequentially only after Bank D is inserted past 102 steps withdrawn (Reference 2). For all practical purposes, this implies that Bank D is the only control bank used for the majority of plant operation.

Table P9-2 contains the final model inputs for Problem 9. The cases for which the input values are endpoints (not averages over the depletion interval) are shown with an asterisk. Table P9-3 contains estimates of the duration of each mid-cycle shutdown period.
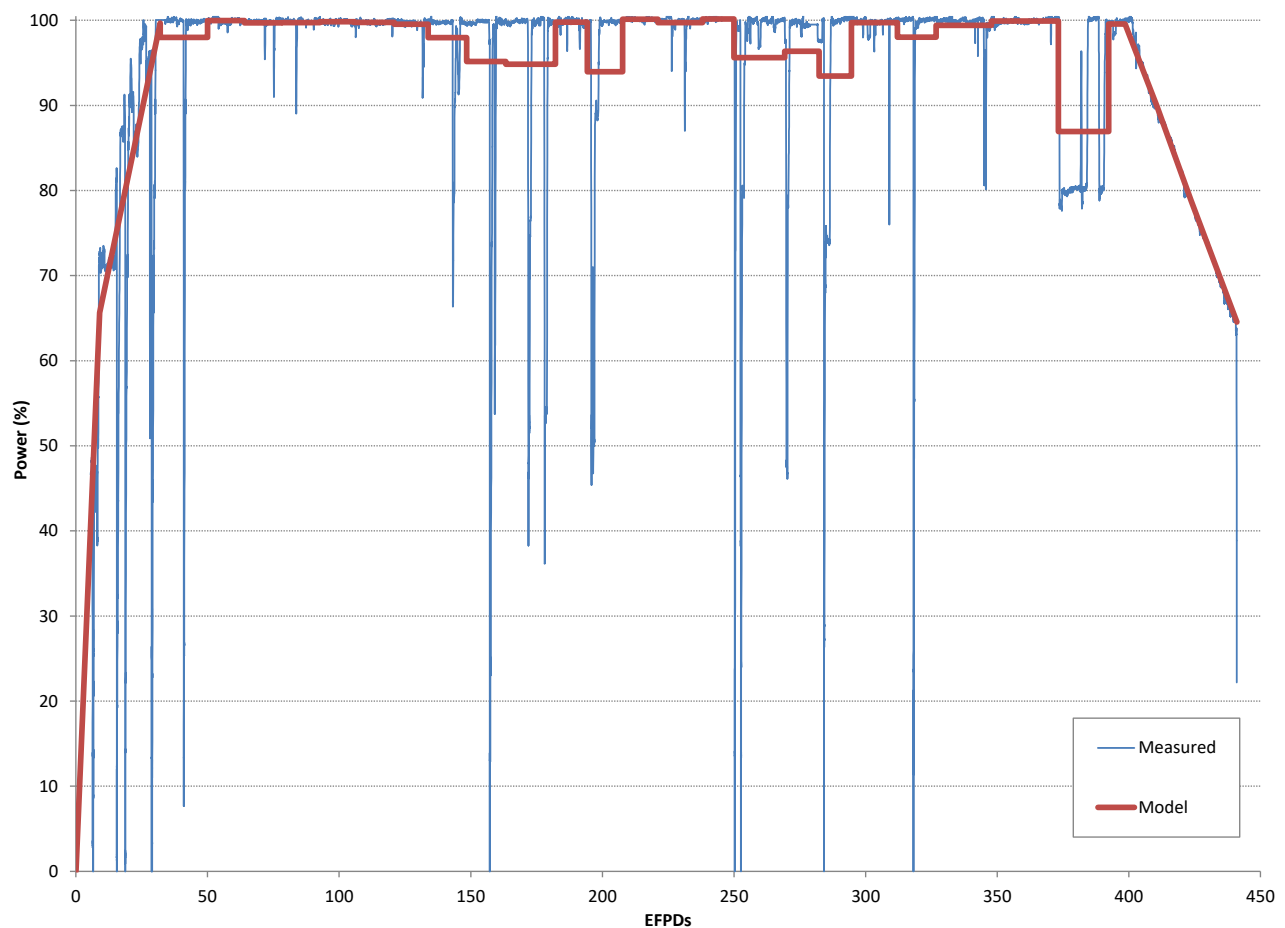
Figure P9-2: Problem 9 Model Input for Reactor Power
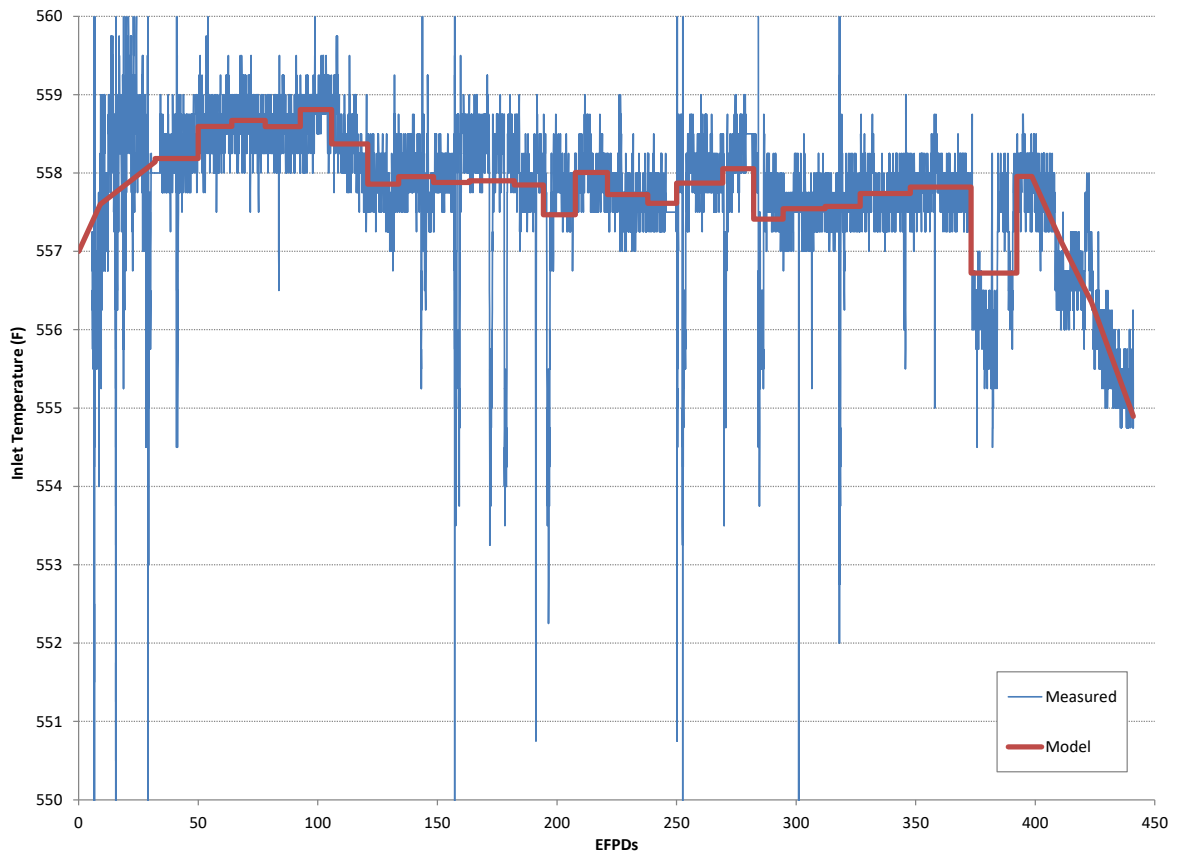
Figure P9-3: Problem 9 Model Input for Core Inlet Temperature
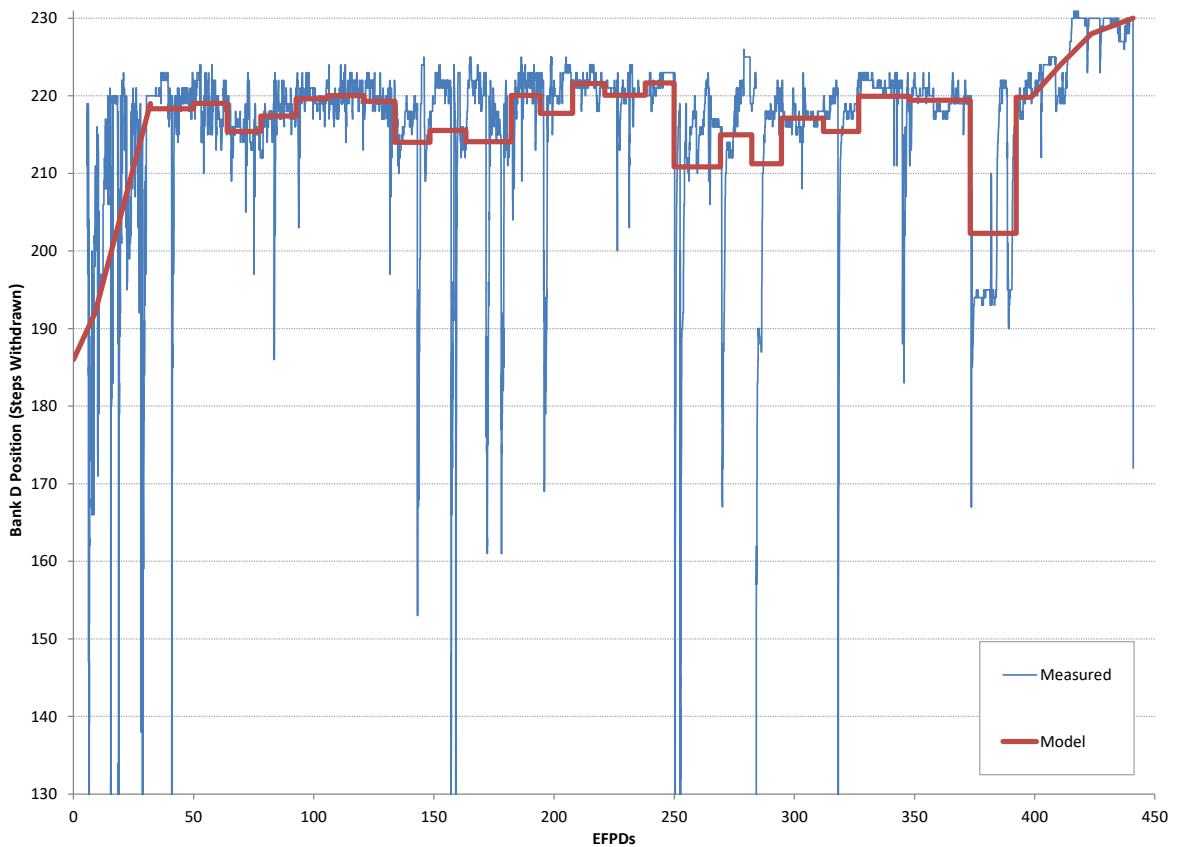
Figure P9-4: Problem 9 Model Input for Control Bank D Positions

Table P9-2: Problem 9 Cycle Depletion Specification

Case	EFPD	Cycle Exposure (GWd/MT)	Power (%)	Inlet Temp. (F)	Bank D Position (steps)
1	0.0	0.000	0.0	557.0	186
2*	9.0	0.346	65.7	557.6	192
3*	32.0	1.229	99.7	558.1	219
4	50.0	1.920	98.0	558.2	218
5	64.0	2.458	100.0	558.6	219
6	78.0	2.996	99.7	558.7	215
7	92.7	3.561	99.7	558.6	217
8	105.8	4.064	99.8	558.8	220
9	120.9	4.644	99.8	558.4	220
10	133.8	5.139	99.5	557.9	219
11	148.4	5.700	98.0	558.0	214
12	163.3	6.272	95.1	557.9	216
13	182.2	6.998	94.8	557.9	214
14	194.3	7.463	99.8	557.8	220
15	207.7	7.978	93.9	557.5	218
16	221.1	8.492	100.1	558.0	222
17	238.0	9.141	99.7	557.7	220
18	250.0	9.602	100.2	557.6	222
19	269.3	10.344	95.6	557.9	211
20	282.3	10.843	96.4	558.1	215
21	294.6	11.315	93.4	557.4	211
22	312.1	11.987	99.7	557.5	217
23	326.8	12.552	98.0	557.6	215
24	347.8	13.359	99.4	557.7	220
25	373.2	14.334	99.9	557.8	219
26	392.3	15.068	86.9	556.7	202
27	398.6	15.310	99.6	558.0	220
28*	410.7	15.775	89.9	557.1	224
29*	423.6	16.270	78.8	556.3	228
30*	441.0	16.939	64.5	554.9	230
Cycle Average			94.0	557.8	216.4

*The statepoint values are endpoints, not averages. If needed,
the average values can be calculated or obtained from the author.

Table P9-3: Problem 9 Approximate Shutdown Durations

Event	EFPD	Duration (days)
1	6.5	3.4
2	15.5	4.8
3	18.8	1.6
4	28.8	0.8
5	28.9	4.7
6	157.2	18.0
7	250.2	1.6
8	252.6	3.7
9	284.1	9.1
10	318.2	1.5

MATERIAL PROPERTIES

All material properties are listed in Section 2 and are the same for Problems 5, 7, and 8.

CAPABILITIES

Successful completion of this benchmark problem can be used to demonstrate the following capabilities:

- Ability to input full cycle operating history (power, flow, RCCAs, etc.)
- Demonstrate ability to perform reactor fuel cycle depletion and isotopic decay
- Ability to handle large volume of data from entire fuel cycle
- Demonstrate parallelism and runtimes for realistic fuel cycle depletions
- Output of cycle results (critical boron concentration, peaking factors, etc.)
- Output of exposure edits
- Demonstrate ability to perform cycle restart for mid-cycle outages or EOC fuel shuffle
- Validate fuel depletion against (coarse) measured plant data

MEASURED RESULTS

The reference for Problem 9 is measured data from the operation of WBN1C1. Currently, these include only the critical soluble boron concentrations measured in the reactor coolant system. The boron-10 content of these measurements is not known, but it can be assumed to initialize at BOC at 19.78 at% (Reference 16). The impact of soluble boron-10 cannot be quantified with the available measured data.

Figure P9-5 and Table P9-4 contain the measured boron concentrations from WBN1C1 provided from TVA in Reference 17. The table also contains the burnup, power, and Bank D position for each measurement following the initial power escalation.

Note that only a subset of the measured boron concentrations fall on model statepoints. For those that do, the model conditions are (mostly) averaged over the depletion interval, while the measured values are snapshot conditions. When comparing, care should be taken to ensure consistency.
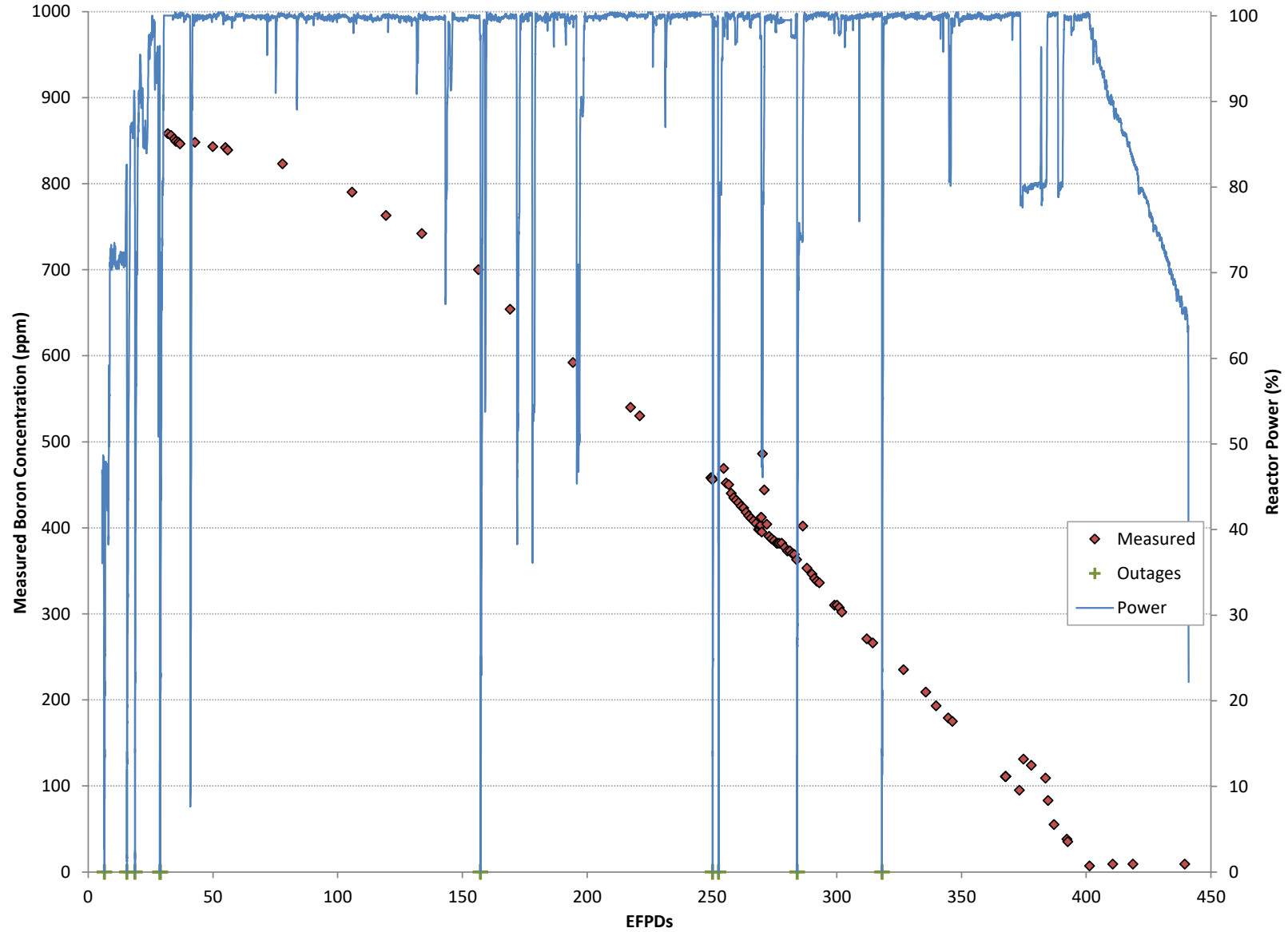
Figure P9-5: Problem 9 Measured Boron Concentrations

Table P9-4: Problem 9 Measured Boron Concentrations (Ref. 17)

EFPD	Power (%)	Bank D (steps)	Boron (ppm)
32.0	99.7	219	858
33.3	99.5	219	856
34.5	99.8	219	852
35.2	99.7	219	849
36.3	100.0	219	848
36.9	99.8	220	846
42.8	100.0	215	848
50.0	99.8	217	843
55.1	99.8	218	842
55.9	99.9	214	839
78.0	99.9	208	823
105.8	99.8	217	790
119.4	99.8	212	763
133.8	99.7	215	742
156.4	99.9	218	700
169.2	99.9	219	654
194.3	98.9	215	592
217.4	100.0	216	540
221.1	99.9	217	530
249.6	99.9	216	458
250.0	100.0	216	458
250.2	99.8	216	456
254.8	99.8	216	469
255.8	97.3	207	452
256.8	99.8	211	450
257.8	100.0	215	440
258.8	99.9	214	435
259.7	97.0	209	432
260.7	100.0	213	429
261.7	100.0	213	425
262.7	99.8	217	423
263.7	100.0	217	418
264.7	99.8	214	414
265.7	100.0	214	411
266.7	99.9	214	408
267.7	99.9	214	405
268.7	100.0	214	398
269.2	99.7	214	398
269.3	97.2	211	402
269.7	97.1	213	403
269.7	82.1	194	412
269.8	47.5	182	412
270.0	47.1	172	395
270.2	46.6	170	486
271.0	95.0	199	444
272.0	99.9	210	404
273.0	100.0	211	390
274.0	99.8	210	387
275.0	100.0	215	385
275.9	99.8	216	382
276.4	97.4	214	382
277.0	97.3	215	382
278.0	96.7	217	382
279.3	97.2	217	377
280.3	97.2	217	373
281.3	97.0	216	373
282.3	97.1	214	370
283.0	97.1	216	369
284.0	99.9	218	363
286.4	89.2	197	402
288.1	99.9	215	353
290.1	99.9	217	346
291.1	99.9	215	341
292.1	100.0	217	338
293.1	100.0	219	336
299.1	98.8	213	310
300.1	100.0	215	310
301.1	97.6	212	307
302.1	100.0	212	302
312.1	100.0	216	271
314.5	99.5	214	266
326.8	99.8	217	235
335.7	99.9	218	209
339.8	100.0	218	193
344.7	99.9	218	179
346.4	100.0	204	175
367.7	100.0	216	111
367.7	100.0	216	111
367.7	100.0	216	111
367.7	100.0	216	111
367.7	100.0	216	111
373.2	99.9	216	95
374.9	79.7	191	131
378.1	79.0	191	124
383.8	80.0	192	109
384.8	100.0	212	83
387.1	99.9	217	55
392.3	100.0	215	38
392.6	99.9	215	35
401.4	99.6	217	7
410.7	89.9	216	9
418.8	83.4	228	9
438.5	65.3	227	9

Table P10-1 provides the details specification of the feed fuel for Cycle 2.

Table P10-1: Problem 10 Fuel Characteristics for Batch 4

	Value	Reference
Fuel Density	10.257 g/cc	Section 2.2
Central Fuel Enrichment	3.709%	2
Blanket Fuel Enrichment (solid)	2.613%	2
Fuel Stack height	144"	Section 1.1
Blanket heights, top and bottom	6"	2
Number of assemblies	84	2
IFBA		
Boron-10 loading	2.355 mg/in	Section 1.9
Coating length	120",132"	2
Coating axial location	centered	2
WABA		
Poison length	132"	2
Poison axial location	centered	2
TPBARs	None	20

Batch 4 has lattice designs containing 48, 104, and 128 IFBA coated fuel rods, with layouts provided in Section 1.9. Additionally, there are WABA designs for 4 and 8 rodlets, with layouts provided in Section 1.10. The core locations of each of these burnable poisons are provided in the shuffle map below.

The WBN1C2 core loading pattern is shown in Figure P10-1. For fresh fuel, the number of IFBA and WABA rodlets are shown (as IFBA|WABA). The long IFBA is indicated with an asterisk. For fuel assemblies shuffled from Cycle 1, the previous cycle core location is provided. The map is shown in quarter symmetry, but a full symmetry map is provided in Appendix K for user convenience.

The length of the refueling outage between Cycles 1 and 2 can be assumed to be 30 days. This will be revised when more data is available and the Cycle 2 measurements are provided.

	H	G	F	E	D	C	B	A
8	H-14	N-13	128*	R-8	128	N-8	L-15	F-11
9	N-3	104	A-9	104|8	B-11	128*	48	C-4
10	128*	G-15	E-15	D-7	104|8	B-7	48	G-10
11	H-1	104|8	J-12	128*	N-2	128	48	F-13
12	128	E-14	104|8	P-3	A-6	104|4	B-4	
13	H-3	128*	J-14	128	104|4		P-6	
14	R-5	48	48	48	M-14	K-2		
15	L-10	M-13	F-9	C-10				

IFBA|WABA or
Previous Cycle 1 Location

Batch 1 - 2.11%

Batch 2 - 2.619%

Batch 3 - 3.1%

Batch 4 - 3.709%

* 132 inch IFBA (All others 120 inch)
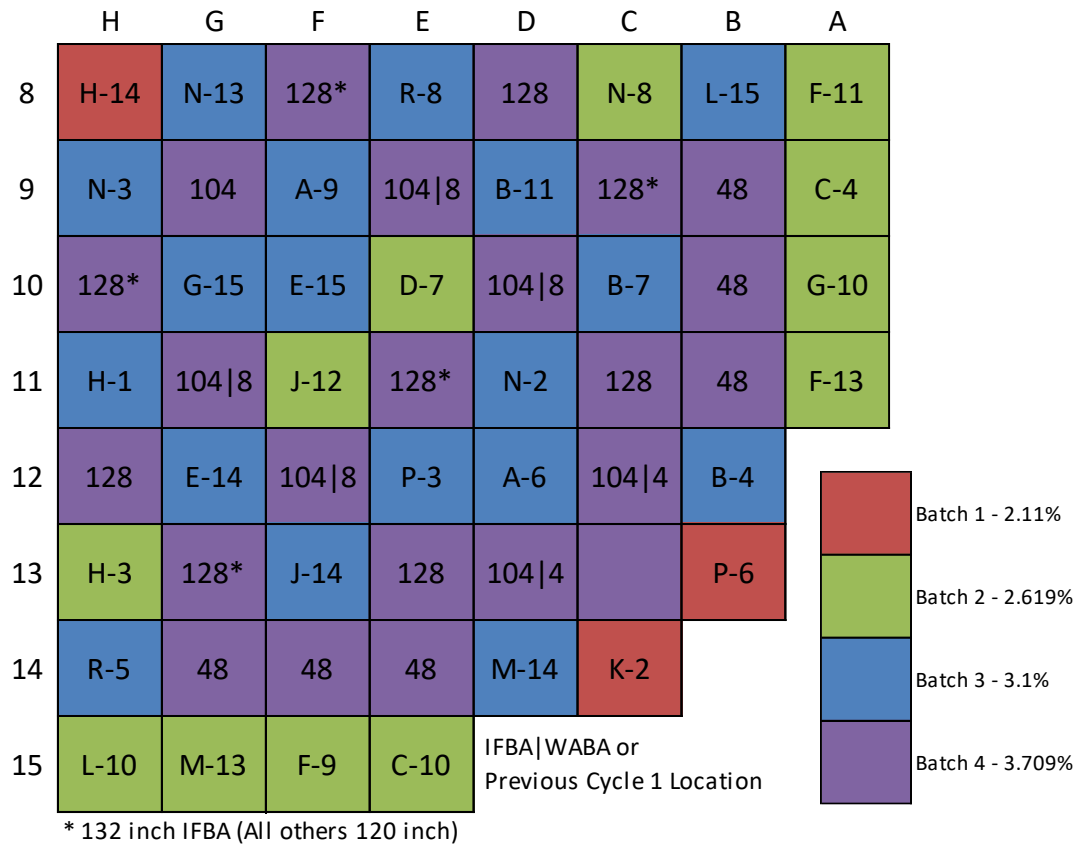
Figure P10-1: Problem 10 WBN1 Cycle 2 Core Loading Pattern

MATERIAL PROPERTIES

All material properties listed in Section 2 are valid for Cycle 2 fuel as well.

CAPABILITIES

Successful completion of this benchmark problem can be used to demonstrate the following capabilities:

- Perform restart from previous statepoint
- Execute reactor refueling by discharging, shuffling, and adding fuel assemblies
- Perform removal of spent burnable absorber assemblies from assemblies which are not discharged from the core
- Account for different axial meshes when loading new fuel types
- Account for fuel isotopic decay during reactor shutdown
- Demonstrate feasibility of using and transferring large restart files
-

REFERENCE SOLUTION

No reference solution exists for Problem 10 at this time. The WBN1 Cycle 2 HZP BOC critical boron or ZPPT test results will be provided in a future revision of this specification.

5. MISCELLANEOUS BENCHMARKS

Problem #4-2D: 2D HZP BOC 3x3 Assembly (Colorset)

This problem is an extension of Problem #2 to investigate fuel assembly interfaces and more realistic control rod effects in 2D. It is a 2D slice from the midplane of Problem #4, which is based on the center nine assemblies in the WBN1 startup core. Successful completion demonstrates the capability to predict the eigenvalue, pin power distribution, and control rod worth for larger 2D configurations.

SPECIFICATIONS

The problem consists of nine Westinghouse 17x17-type fuel assemblies arranged in a 3x3 checkerboard pattern directly from the center of the WBN1 initial loading pattern (Sections 1.1 to 1.8 and 1.12). The fuel is at beginning-of-life (BOL) and Hot Zero Power (HZP) isothermal conditions. In addition to the same materials as Problem #2, this problem also tests the ability to define and place Pyrex (1.5), AIC, and B_4C (1.6) absorbers in the assembly guide tubes.

Figure M1-1 provides the loading pattern for this problem, simply from the axial midplane and center of the WBN1 core described in Section 1.12 and Reference 1. In this figure, Region 1 is represented by the 2.11% enrichment with center RCCA, and Region 2 is the 2.619% enriched region with the 20 Pyrex rods. This problem is ideally run in quarter or octant symmetry.
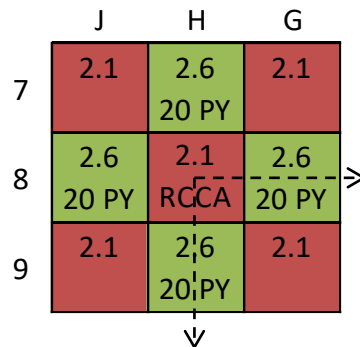
Figure M1-1: Problem 4-2D Assembly, Poison, and Control Layout

Table M1-1: Problem 4-2D Input Specification

Input	Value	Section
Fuel Density	10.257 g/cc	2.2
Fuel Enrichment – Region 1	2.11%	2.1
Fuel Enrichment – Region 2	2.619%	2.1
Power	0% FP	--
Inlet Coolant Temperature	600 K	--
Inlet Coolant Density	0.743 g/cc	2.0
Reactor Pressure	2250 psia	3.
Boron Concentration	1300 ppm	3.

- The fuel enrichments are directly from the as-built values from the WBN1 initial loading (Reference 1) and are the same as Problem #4.
- The fuel density is chosen to account for dishes and chamfers in the pellet stack.
- The moderator density corresponds to 565K at the core pressure. (Reference 4).

- 600K is used for coolant and cladding temperatures rather than 565K to be consistent with available CE cross section libraries (at the time).
- The 20 Pyrex pattern (Section 1.5) does not include thimble plugs since this problem is a 2D slice at the core midplane.
- Both AIC and B₄C control rods are inserted into the center assembly.

MATERIAL PROPERTIES

All material properties are listed in Section 2 and are the same as Problem #4.

CAPABILITIES

The capabilities demonstrated by this problem are the same as Problem #2 plus the addition of multiple assemblies and poison rod placement. This problem is a more accurate depiction of the thermal flux suppression in PWRs due to control rods than is performed in the single assembly analysis. It can also be used to validate the pin power distributions at the intersections of multiple assembly types.

REFERENCE SOLUTION

The reference values for this benchmark problem are calculated by the SCALE 6.2 Beta (Ref. 6) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The CSAS6 sequence for KENO-VI uses input which includes materials, densities, fuel isotopics, an exact geometry description, and other code options. For this problem, KENO-VI can provide an approximate eigenvalue solution within a small range of uncertainty using the precise geometry specification and without multi-group cross section approximations. It can also perform fission rate tallies for each fuel rod, which can be normalized and post-processed to produce the pin power distribution as well as a distribution of uncertainties. This problem is performed at 600K isothermal conditions so no temperature adjustment is required.

Cross Sections

The reference solution is based on ENDF/B-VII.0 CE cross sections as obtained from SCALE 6.2 (**ce-v7-endf**) (Ref. 6). Results for SCALE CE ENDF/B-VI.8 cross sections are included in Appendix H. Only 600K cross sections are used for these results, but results for 565K cases are included in Appendix H.

Materials

The SCALE 6 material processor MIPLIB allows common input of compositions across most SCALE codes and sequences. For this problem, the materials are input nearly as described in this specification.

- The fuel isotopes are calculated based on the equations in Table 17 (and Ref. 5) and are provided here.

Table M1-2: Problem 4-2D Calculated Fuel Isotopic Input vs. Enrichment

Isotope	Region 1 Wt%	Region 2 Wt%
U-234	0.0174%	0.0219%
U-235	2.11%	2.619%
U-236	0.0097%	0.0120%
U-238	97.8629%	97.3471%

*Note that explicit O-16 is not needed in MIPLIB input

- For the reference calculations, the pellet-clad gap is modeled explicitly as Helium with nominal density. This could also be modeled as 'void' or air. Other gaps in control and absorber rods are handled in the same manner.
- The boron concentration is input by use of weight fractions with the H_2O and boron MIPLIB compositions. For 1300 ppm, the corresponding weight fraction is 0.0013, and the water fraction is 0.9987.
- The MIPLIB default material for Pyrex is not used but rather the isotopes are input explicitly per Section 1.5.
- Because this problem is 2D, spacer grids are not modeled.

Parameters

In order to get the power distribution uncertainty as low as possible for the lower powered fuel rods (adjacent to control rods) an extremely large number of particles must be used. In this case, 4e9 particles are used, 2000 generations with 2e6 particles per generation, skipping 200 generations. This resulted in an eigenvalue uncertainty of less than 1.3 pcm, and a maximum estimated uncertainty in any fuel rod of 0.071%.

Geometry

The pin cell geometry will be modeled explicitly with concentric fuel, gap, and cladding cylinders using the radii provided in Section 1. The lattices are modeled according to Section 1.2. The 3x3 arrangement of assemblies is modeled in quarter symmetry with reflective boundary conditions. Each of the burnable poisons and discrete inserts are modeled as described in Section 1. The radial layout of the individual lattices is chosen based on the center of the core loading in Section 1.12. Figure M1-2 shows the KENO geometry with RCCA in the center location.
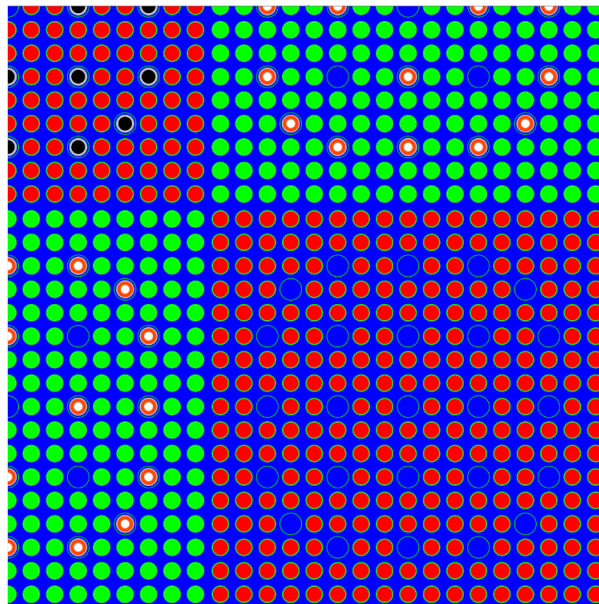
Figure M1-2: Problem 4-2D Radial Geometry

Input Files

The CE KENO-VI input files for this problem are unreasonably large to be included in this document. They are located on cpile2.ornl.gov in location **/home/agm/vera/**.

Computer Code

The reference calculations were executed with SCALE 6.2 Beta 2 on the Fission supercomputer at Idaho National Laboratory. The approximate run time for the initial case was 20 hours on 260 cores, utilizing up to 2.5 GB of memory per core.

Mixing Table

The following table provides the precise isotopic number densities used for each mixture in the reference problems.

Table M1-3: Reference Mixing Table

Material	Isotope ID	Atom Density (/barn-cm)
2.11% Fuel	8016	4.57591E-02
	92234	4.04814E-06
	92235	4.88801E-04
	92236	2.23756E-06
	92238	2.23844E-02
2.619% Fuel	8016	4.57617E-02
	92234	5.09503E-06
	92235	6.06709E-04
	92236	2.76809E-06
	92238	2.22663E-02
Gap	2004	2.68714E-05
Cladding	24050	3.30121E-06
	24052	6.36606E-05
	24053	7.21860E-06
	24054	1.79686E-06
	26054	8.68307E-06
	26056	1.36306E-04
	26057	3.14789E-06
	26058	4.18926E-07
	40090	2.18865E-02
	40091	4.77292E-03
	40092	7.29551E-03
	40094	7.39335E-03
	40096	1.19110E-03
	50112	4.68066E-06
	50114	3.18478E-06
	50115	1.64064E-06
	50116	7.01616E-05
	50117	3.70592E-05
	50118	1.16872E-04
	50119	4.14504E-05
	50120	1.57212E-04
	50122	2.23417E-05
	50124	2.79392E-05
	72174	3.54138E-09
	72176	1.16423E-07
	72177	4.11686E-07
	72178	6.03806E-07
	72179	3.01460E-07
	72180	7.76449E-07

Material	Isotope ID	Atom Density (/barn-cm)
Moderator 0.743 g/cc	8016	2.48112E-02
	1001	4.96224E-02
	5010	1.07070E-05
	5011	4.30971E-05
Pyrex	5010	9.63266E-04
	5011	3.90172E-03
	8016	4.67761E-02
	14028	1.81980E-02
	14029	9.24474E-04
	14030	6.10133E-04
SS304	6000	3.20895E-04
	14028	1.58197E-03
	14029	8.03653E-05
	14030	5.30394E-05
	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
AIC	47107	2.36159E-02
	47109	2.19403E-02
	48106	3.41523E-05
	48108	2.43165E-05
	48110	3.41250E-04
	48111	3.49720E-04
	48112	6.59276E-04
	48113	3.33873E-04
	48114	7.84957E-04
	48116	2.04641E-04
	49113	3.44262E-04
	49115	7.68050E-03
B₄C	5010	1.52689E-02
	5011	6.14591E-02
	6000	1.91820E-02

REFERENCE SOLUTION RESULTS

Three cases were executed, including uncontrolled, AIC, and B$_4$C controlled cases, and the eigenvalues, pin powers, assembly powers, and control rod reactivity worths are provided below. The presented results are based on ENFDF/B-VII cross sections, but the ENDF/B-VI results are included in Appendix H (for 4A-2D and 4B-2D). Additionally, eigenvalues and assembly powers for the same geometry at 565K are also included in the Appendix. The control rod reactivity worth calculation is done as:

$$\rho_{CRD} = \left(\frac{1}{k_{UNC}} - \frac{1}{k_{CON}} \right) \times 10^5 \ [pcm]$$

Also, note that the reference KENO-VI results are calculated for a quadrant, but are collapsed to octant geometry. The symmetric fuel rod powers are averaged, and the symmetric sigmas are averaged and divided by the square root of two, as the estimate of the uncertainty is inversely proportional to the square root of the population size.

Table M1-4: Problem 4-2D Reference Solution Results

Case	Description	k-effective	Rod Worth (pcm)
4A-2D	Uncontrolled	1.010238 ± 0.000013	--
4B-2D	AIC Controlled	0.983446 ± 0.000012	2697 ± 2
4C-2D	B4C Controlled	0.980291 ± 0.000013	3024 ± 2

Table M1-5: Problem 4-2D Reference Solution Power Statistics

Powers	Quantity	4A-2D	4B-2D	4C-2D
Assembly Powers	Maximum	1.07795	1.18148	1.19428
	Average Uncertainty	0.004%	0.006%	0.006%
Pin Powers	Maximum	1.19371	1.35679	1.37729
	Average Uncertainty	0.034%	0.034%	0.034%
	Maximum Uncertainty	0.052%	0.067%	0.071%
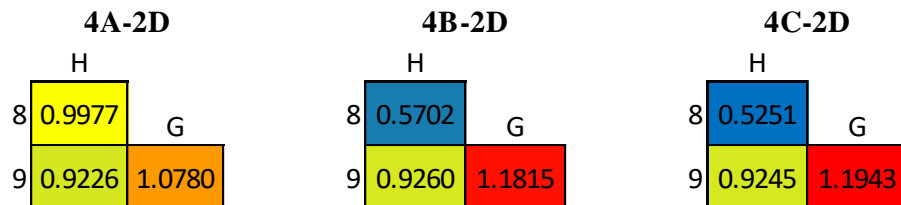
Figure M1-3: Problem 4-2D Assembly Power Distributions
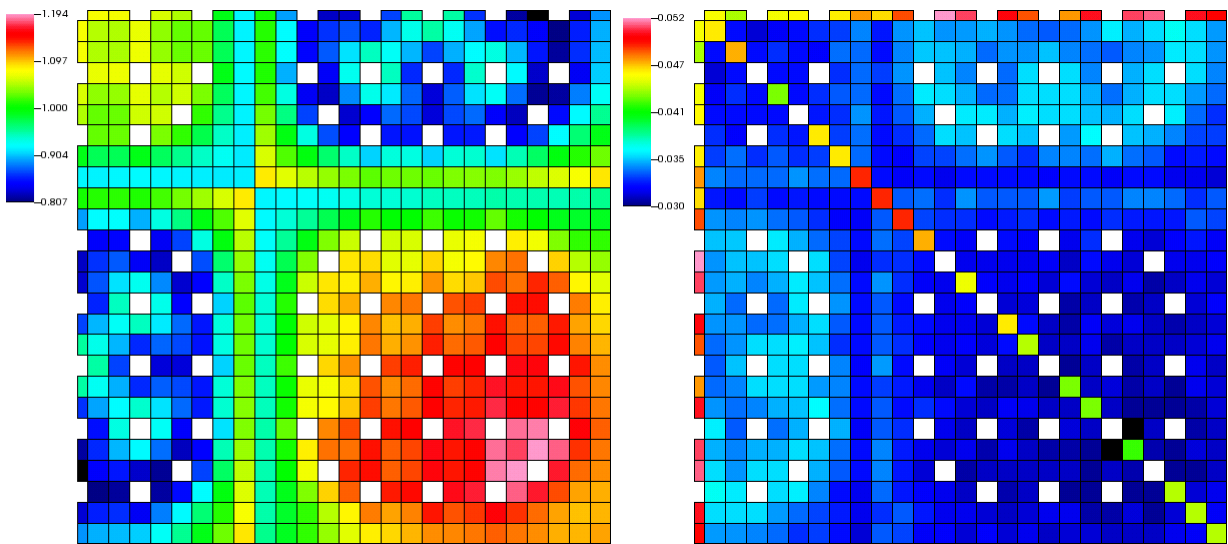
Figure M1-4: Problem 4A-2D Fission Rate and Uncertainty (%) Distribution
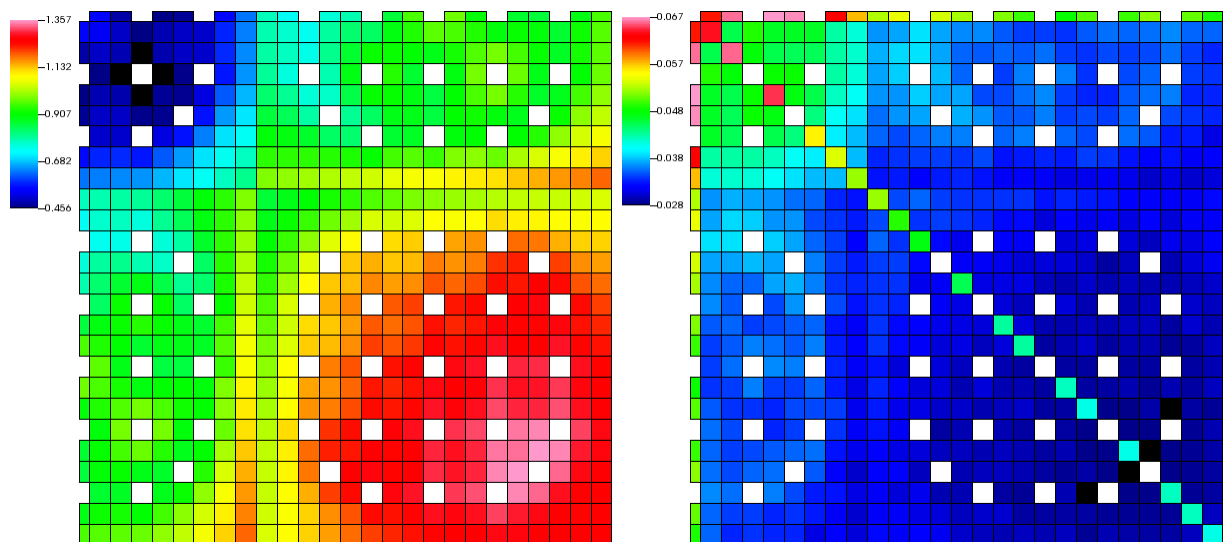
Figure M1-5: Problem 4B-2D Fission Rate and Uncertainty (%) Distribution
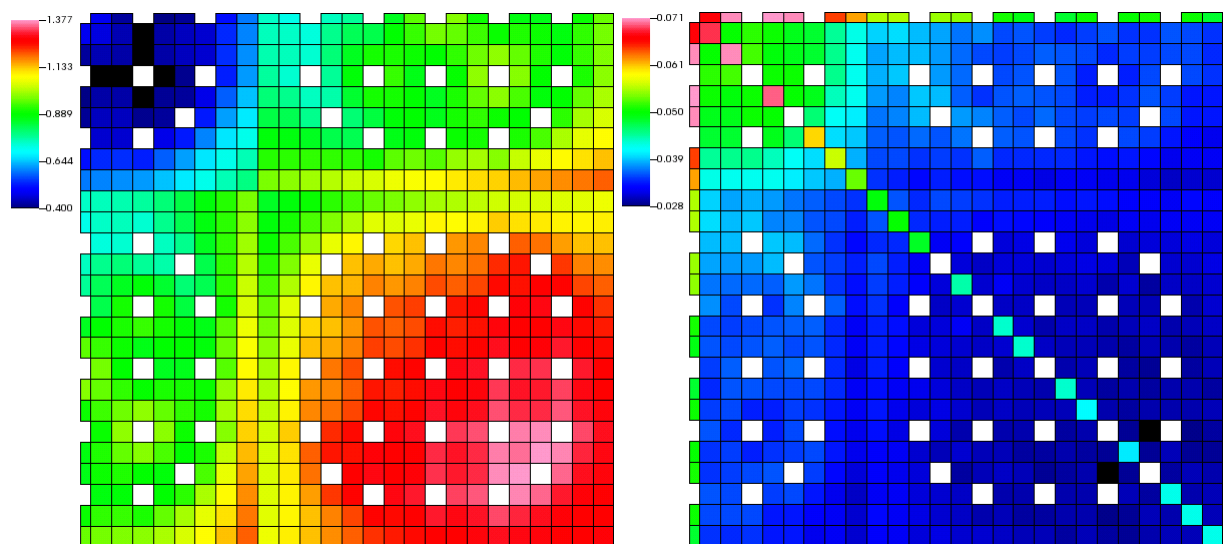
Figure M1-6: Problem 4C-2D Fission Rate and Uncertainty (%) Distribution

Problem #REF1-2D: 2D HZP BOC Reflector – Case 1

This problem is designed to investigate the neutron flux leakage out of the east boundary of the WBN1 initial core. Typical neutronics methods refer to this as a "reflector" calculation because the purpose is usually to supply boundary conditions for other coarser methods such as nodal diffusion. These regions are challenging to simulate due to the large thermal flux gradient at the core edge, the ability for neutrons to leave one assembly and enter a neighboring one by passing though the outer region, and the difficulty in modeling the core structural components that may influence the neutron moderation or scatter probabilities.   Simulation with a CE Monte Carlo method is a rigorous way to validate the assumptions made by other methods for this scenario.

The geometry is a 2D slice at the midplane of six of the peripheral fuel assemblies of WBN1 as prescribed in Section 1.12. The core baffle is modeled explicitly, with outside moderator and an outer non-reentrant condition (vacuum) . Successful completion demonstrates the capability to predict the eigenvalue and pin power distribution of this configuration. Successful prediction of the outer-most fuel rod powers (which are very low powers) implies accurate prediction of the peripheral assembly surface conditions.

SPECIFICATIONS

The problem consists of six Westinghouse 17x17-type fuel assemblies arranged in a 2x3 pattern directly from the east edge of the WBN1 initial loading pattern shown in Section 1.12 (Ref. 1). The fuel is at beginning-of-life (BOL) and Hot Zero Power (HZP) isothermal conditions. Outside of the fuel exists a 21.5 cm thickness of moderator, with the core baffle explicitly modeled as described in Section 1.13, effectively creating a 3x3 geometry. The other core structural components are not modeled.

Figure M2-1 provides the loading pattern for this problem, simply from the center of the WBN1 core described in Reference 1. In this figure, Region 1 is represented by the 2.11% enrichment, and Region 2 is the 3.10% enriched region with the indicated number of Pyrex rods. This problem must be run in full symmetry.
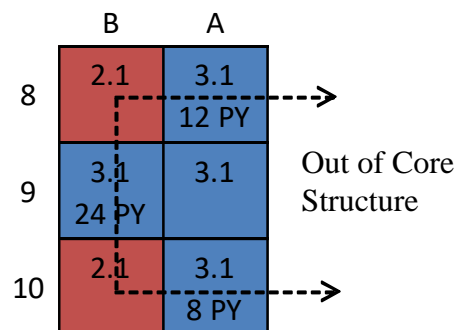
Figure M2-1: Problem REF1-2D Assembly and Poison Configuration

Table M2-1: Problem REF1-2D Input Specification

Input	Value	Section
Fuel Density	10.257 g/cc	2.2
Fuel Enrichment – Region 1	2.11%	2.1
Fuel Enrichment – Region 2	3.10%	2.1
Power	0% FP	--
Inlet Coolant Temperature	600 K	--
Inlet Coolant Density	0.743 g/cc	2.0
Reactor Pressure	2250 psia	3.
Boron Concentration	1300 ppm	3.

- The fuel enrichments are directly from the as-built values from the WBN1 initial loading (Reference 1).
- The fuel density is chosen to account for dishes and chamfers in the pellet stack.
- The moderator density corresponds to 565K at the core pressure. (Reference 4).
- 600K is used for coolant and cladding temperatures rather than 565K to be consistent with available CE cross section libraries
- The Pyrex patterns (Section 1.5) do not include thimble plugs since this problem is a slice at the core midplane.

MATERIAL PROPERTIES

All material properties are listed in Section 2.

CAPABILITIES

This problem demonstrates the capability to match reactivity and pin powers for a difficult neutron flux distribution created by leakage from the reactor core. Accurate prediction of edge pin powers implies good performance in predicting the flux on the non-reentrant surface of the core.

REFERENCE SOLUTION

The reference results for this benchmark problem are calculated by the development version of the SCALE 6.2 (Ref. 6) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The development version is used instead of the last released version in order to utilize new parallel capabilities that permit much larger numbers of particle histories. The input to the CSAS6 sequence which uses KENO-VI includes materials, densities, fuel isotopics, an exact geometry description, and other code options. For this problem, KENO-VI can provide an approximate eigenvalue solution within a small range of uncertainty using the precise geometry specification and without multi-group cross section approximations. It can also perform fission rate tallies for each fuel rod, which can be normalized and post-processed to produce the pin power distribution as well as a distribution of uncertainties. This problem is performed at 600K isothermal conditions so no temperature adjustment is required.

Cross Sections

The reference solution is based on ENDF/B-VII.0 CE cross sections as obtained from the SCALE 6.2 development version (**ce-v7-endf**) (Ref. 6).   ENDF/B-VI.8 cross sections are not included in this problem.

Materials

The SCALE 6 material processor MIPLIB allows common input of compositions across most SCALE codes and sequences. For this problem, the materials are input nearly as described in this specification.

- The fuel isotopes are calculated based on the equations in Table 17 (and Ref. 5) and are provided here.

Table M2-2: Problem REF1-2D Calculated Fuel Isotopic Input vs. Enrichment

Isotope	Region 1 Wt%	Region 2 Wt%
U-234	0.0174%	0.0263%
U-235	2.11%	3.1000%
U-236	0.0097%	0.0143%
U-238	97.8629%	96.8594%

*Note that explicit O-16 is not needed in MIPLIB input

- For the reference calculations, the pellet-clad gap is modeled explicitly as Helium with nominal density. This could also be modeled as 'void' or air. Other gaps in control and absorber rods are handled in the same manner.
- The boron concentration is input by use of weight fractions with the H_2O and boron MIPLIB compositions. For 1300 ppm, the corresponding weight fraction is 0.0013, and the water fraction is 0.9987.
- The MIPLIB default material for pyrex is not used but rather the isotopes are input explicitly per Section 1.5.
- The baffle is modeled using the default miplib material for SS304, which is the same material as used for the pyrex rods.
- Because this problem is 2D, spacer grids are not modeled.

Parameters

In order to get the power distribution uncertainty as low as possible for the low powered fuel rods on the core periphery an extremely large number of particles must be used. In this case, 1.5e9 particles are used, skipping 200 generations. This resulted in an eigenvalue uncertainty of **2 pcm**. The maximum estimated uncertainty in pin powers is provided below as a function of pin power level.

Table M2-3: Problem REF1-2D Maximum Pin Power Uncertainty vs. Pin Power

Pin Power Range	Maximum Estimated Fractional Uncertainty
0.0 < 0.5	0.18%
0.5 – 1.0	0.17%
> 1.0	0.12%

Geometry

The pin cell geometry will be modeled explicitly with concentric fuel, gap, and cladding cylinders using the radii provided in Section 1. The lattices are modeled according to Section 1.2. The 3x3 arrangement of assemblies and moderator is modeled in full symmetry with reflective boundary conditions at the centers of assemblies on the north, west, and south surfaces in order to provide a realistic power distribution similar to that of WBN1. The moderator and baffle in the reflector region is modeled as 21.5 cm thick (same as fuel assembly) with an explicit steel slab for the baffle.

Each of the burnable poisons and discrete inserts are modeled as described in Section 1. Figure M2-2 shows the KENO geometry.

Note that the baffle geometry is slightly different from that described in Section 1.13. The fuel baffle gap was mistakenly taken as **0.142 cm** (rather than 0.19) and the baffle thickness was mistakenly taken as **2.858 cm** (rather than 2.85 cm). This will be corrected in a future revision to this specification.
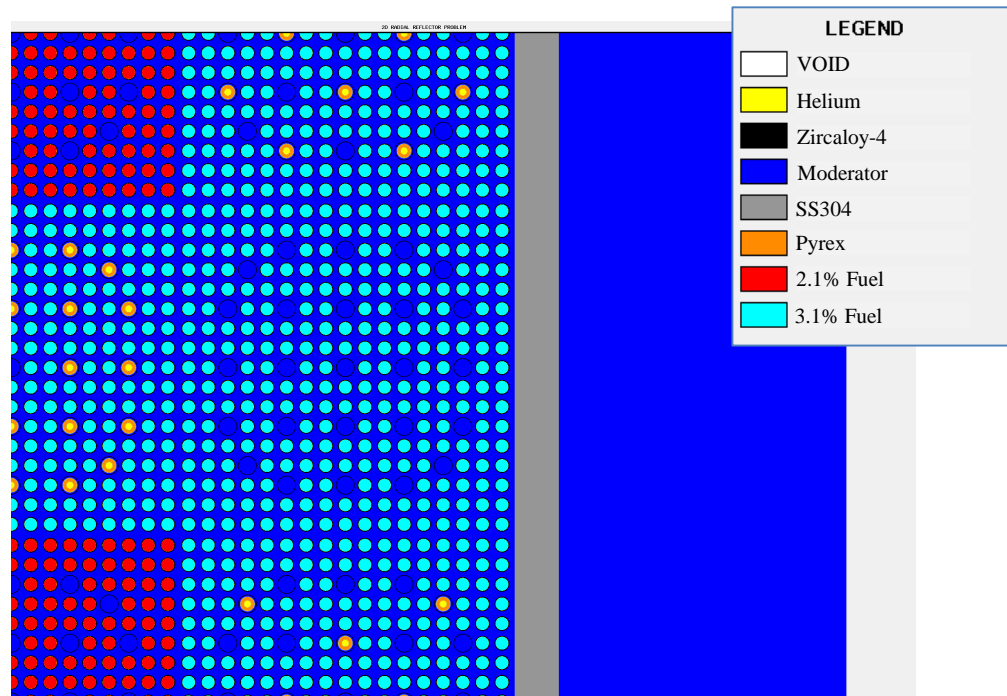
Figure M2-2: Problem REF1-2D Radial Geometry

Input Files

The CE KENO-VI input files for this problem are unreasonably large to be included in this document. They are located on cpile2.ornl.gov in location **/home/agm/vera/**.

Computer Code

The reference calculations were executed with the development version of SCALE 6.2 on cpile2.ornl.gov from location **/scale/scale_dev/staging-mpi**. These calculations ran on ~96 processors for ~16 hours.

Mixing Table

The following table provides the precise isotopic number densities used for each mixture in the reference problems.

Table M2-4: Reference Mixing Table

Material	Isotope ID	Atom Density (/barn-cm)
2.11% Fuel	8016	4.57591E-02
	92234	4.04814E-06
	92235	4.88801E-04
	92236	2.23756E-06
	92238	2.23844E-02
3.10% Fuel	8016	4.57642E-02
	92234	6.11864E-06
	92235	7.18132E-04
	92236	3.29861E-06
	92238	2.21546E-02
Gap	2004	2.68714E-05
Cladding	24050	3.30121E-06
	24052	6.36606E-05
	24053	7.21860E-06
	24054	1.79686E-06
	26054	8.68307E-06
	26056	1.36306E-04
	26057	3.14789E-06
	26058	4.18926E-07
	40090	2.18865E-02
	40091	4.77292E-03
	40092	7.29551E-03
	40094	7.39335E-03
	40096	1.19110E-03
	50112	4.68066E-06
	50114	3.18478E-06
	50115	1.64064E-06
	50116	7.01616E-05
	50117	3.70592E-05
	50118	1.16872E-04
	50119	4.14504E-05
	50120	1.57212E-04
	50122	2.23417E-05
	50124	2.79392E-05
	72174	3.54138E-09
	72176	1.16423E-07
	72177	4.11686E-07
	72178	6.03806E-07
	72179	3.01460E-07
	72180	7.76449E-07

Material	Isotope ID	Atom Density (/barn-cm)
Moderator 0.743 g/cc	8016	2.48112E-02
	1001	4.96224E-02
	5010	1.07070E-05
	5011	4.30971E-05
Pyrex	5010	9.63266E-04
	5011	3.90172E-03
	8016	4.67761E-02
	14028	1.81980E-02
	14029	9.24474E-04
	14030	6.10133E-04
SS304	6000	3.20895E-04
	14028	1.58197E-03
	14029	8.03653E-05
	14030	5.30394E-05
	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

REFERENCE SOLUTION RESULTS

Both controlled and uncontrolled cases were executed and the eigenvalues, pin powers, and assembly powers are provided below without any collapse due to symmetry. Detailed results in ASCII form are included in Appendix I.

The eigenvalue of calculated by CE KENO-VI for this case was **0.993677 ± 0.000021**.

Table M2-5: Problem REF1-2D Reference Solution Power Statistics

Powers	Quantity	Values
Assembly Powers	Maximum	1.1470
	Average Uncertainty	0.092%
	Maximum Uncertainty	0.100%
Pin Powers	Maximum	1.3705
	Average Uncertainty	0.092%
	Maximum Uncertainty	0.180%

Powers

	B	A
8	1.0998	0.8590
9	1.0813	0.9981
10	1.1470	0.9402

Uncertainties

	B	A
8	0.086%	0.100%
9	0.087%	0.091%
10	0.085%	0.095%
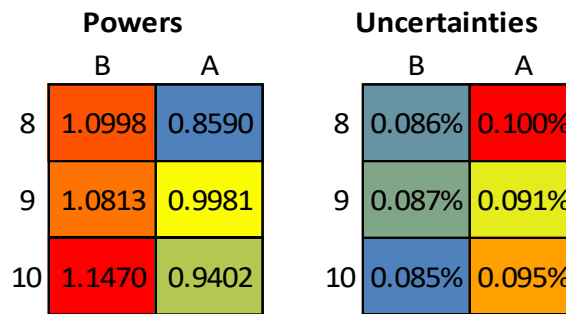
Figure M2-3: Problem REF1-2D Assembly Power Distributions

Figure M2-4: Problem REF1-2D Pin Power Distribution

Figure M2-5: Problem REF1-2D Pin Power Estimated Uncertainties

Problem #5-2D: 2D HZP BOC Quarter Core

This problem is an entire 2D slice of the WBN1 startup core. Successful completion demonstrates the capability to predict the eigenvalue, pin power distribution, and control rod worth for a 2D full core configuration, and includes complex effects such as neutron flux suppression from regulating control rods and neutron flux leakage and reflection at the core baffle.

SPECIFICATIONS

The problem consists of a complete quarter core loading of Westinghouse 17x17-type fuel assemblies arranged in the WBN1 initial loading pattern (Sections 1.1 to 1.8 and 1.12). The fuel is at beginning-of-life (BOL) and Hot Zero Power (HZP) isothermal conditions. The core baffle, barrel, vessel, and neutron pads are all included explicitly in the radial reflector (Section 1.13). In addition to the same materials as Problems #2 and #4-2D, this problem also tests the ability to define and place Pyrex (1.5) and AIC and B_4C (1.6) absorbers in the assembly guide tubes, and the ability to model the core baffle and other core structures.

Figure M3-1 provides the complete core loading pattern in quarter core symmetry. Only Bank D is used in the problem. For Bank D, both AIC and B_4C sections are utilized. Incore instrumentation is NOT included.
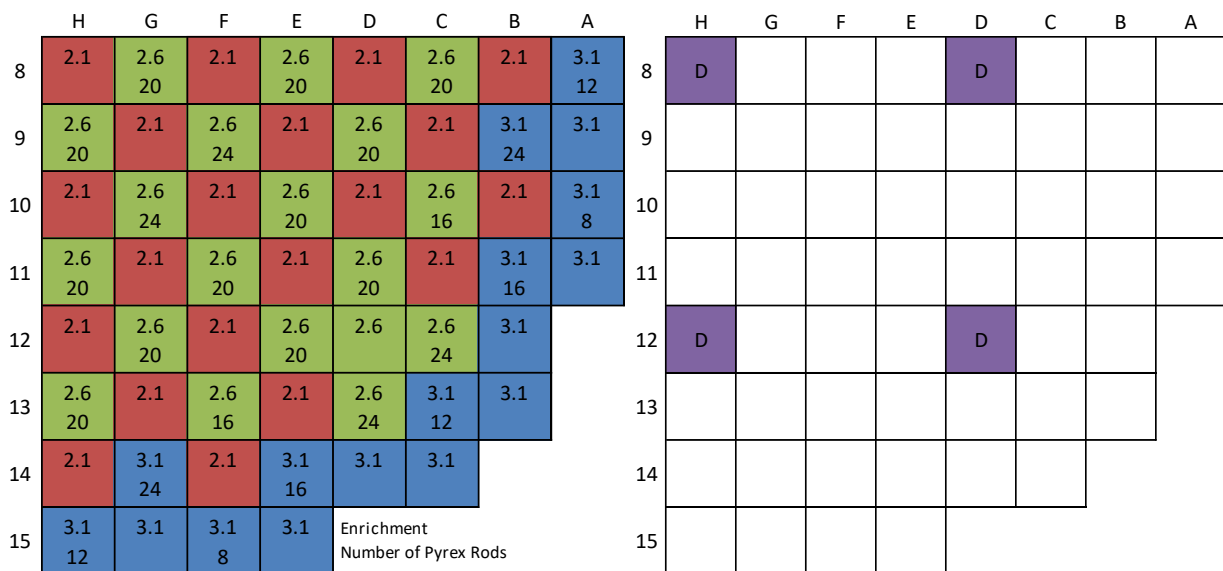
Figure M3-1: Problem 5-2D Assembly, Poison, and Control Rod Layout
(Quarter Symmetry)

Table M3-1: Problem 5-2D Input Specification

Input	Value	Section
Fuel Density	10.257 g/cc	2.2
Fuel Enrichment – Region 1	2.11%	2.1
Fuel Enrichment – Region 2	2.619%	2.1
Fuel Enrichment – Region 3	3.10%	2.1
Power	0% FP	--
Inlet Coolant Temperature	565 K	--
Inlet Coolant Density	0.743 g/cc	2.0
Reactor Pressure	2250 psia	3.
Boron Concentration	1300 ppm	3.
RCCA Bank Utilized	Bank D	1.12

- The fuel enrichments are directly from the as-built values from the WBN1 initial loading (Section 1.12 and Reference 1) and are the same as Problems #5.
- The fuel density is chosen to account for dishes and chamfers in the pellet stack.
- The moderator temperature and density corresponds to 565K at the core pressure. (Reference 4).
- The Pyrex patterns (Section 1.5) do not include thimble plugs since this problem is a 2D slice at the core midplane.

MATERIAL PROPERTIES

All material properties are listed in Section 2 and are the same as Problem #5 (yet undefined).

CAPABILITIES

The capabilities demonstrated by this are the eigenvalue, pin power distribution, and control rod worth of a complete 2D slide of a reactor core, including the following capabilities:

- Support explicit baffle geometry and radial vacuum boundary condition
- Support quarter core rotational symmetry about core axes
- Provide automatic optimized domain and energy decomposition for parallelization
- Validate eigenvalue and pin powers verses Monte Carlo methods for radial core leakage conditions.

REFERENCE SOLUTION

The reference values for this benchmark problem are calculated by the SCALE 6.2 Beta (Ref. 6) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The CSAS6 sequence for KENO-VI uses input that includes materials, densities, fuel isotopics, an exact geometry description, and other code options. For this problem, KENO-VI can provide an approximate eigenvalue solution within a small range of uncertainty using the precise geometry specification. It can also perform fission rate tallies for each fuel, which can be normalized and post-processed to produce the pin power distribution as well as a distribution of uncertainties.

Cross Sections

The reference solution is based on ENDF/B-VII.0 CE cross sections as obtained from SCALE 6.2 (**ce-v7-endf**) (Ref. 6). Only 565K cross sections are utilized. For the isotope H-1, the $S(\alpha,\beta)$ scattering data is not interpolated internally and is only available at 550K and 600K. Therefore a secondary calculation was performed and the final results include a manually calculated correction factor (-43 pcm).

Materials

The SCALE 6 material processor MIPLIB allows common input of compositions across most SCALE codes and sequences. For this problem, the materials are input as described in this specification.

- The fuel isotopes are calculated based on the equations in Table 17 (and Ref. 5) and are provided here.

Table M3-2: Problem 5-2D Calculated Fuel Isotopic Input vs. Enrichment

Isotope	Region 1 Wt%	Region 2 Wt%	Region 3 Wt%
U-234	0.0174%	0.0219%	0.0263%
U-235	2.11%	2.619%	3.10%
U-236	0.0097%	0.0120%	0.0143%
U-238	97.8629%	97.3471%	96.8594%

*Note that explicit O-16 is not needed in MIPLIB input

- For the reference calculations, the pellet-clad gap is modeled explicitly as Helium with nominal density. This could also be modeled as 'void' or air. Other gaps in control and absorber rods are handled in the same manner.
- The boron concentration is input by use of weight fractions with the H_2O and boron MIPLIB compositions. For 1300 ppm, the corresponding weight fraction is 0.0013, and the water fraction is 0.9987.
- The MIPLIB default material for Pyrex is not used but rather the isotopes are input explicitly per Section 1.5.
- Because this problem is 2D, spacer grids are not modeled.
- SS304 is used for all core structure components except for the vessel itself, which uses carbon steel.

Parameters

In order to get the power distribution uncertainty as low as possible for the lower powered fuel rods at the edge of the core, an extremely large number of particles must be used. In this case, 25e9 particles are used, with 5000 generations of 5e6 particles per generation, skipping 250 generations. This resulted in an eigenvalue uncertainty of less than **0.5 pcm** and an average pin power uncertainty of **0.06%**. The maximum estimated uncertainty in pin powers is provided below as a function of pin power level.

Table M3-3: Problem 5-2D Maximum Pin Power Uncertainty vs. Pin Power

Pin Power Range	Maximum Estimated Fractional Uncertainty		
	5A-2D	5B-2D	5C-2D
$0.0 < 0.5$	0.14%	0.14%	0.15%
$0.5 - 1.0$	0.11%	0.12%	0.12%
> 1.0	0.09%	0.09%	0.09%

Geometry

The pin cell geometry will be modeled explicitly with concentric fuel, gap, and cladding cylinders using the radii provided in Section 1. The lattices are modeled according to Section 1.2. The core loading pattern is described in Section 1.12 and is modeled in quarter symmetry with reflective boundary conditions. The radial reflector is modeled explicitly as described in Section 1.13. Each of the burnable poisons and discrete inserts are modeled as described in Section 1. Figure M3-1 shows the KENO geometry and control bank locations.

A sensitivity study has been performed on the effects of the radial core structure in Appendix J. These include the eigenvalues and pin power distributions (on request from the author) for cases without some of the radial reflector detail (i.e. no barrel or pad).
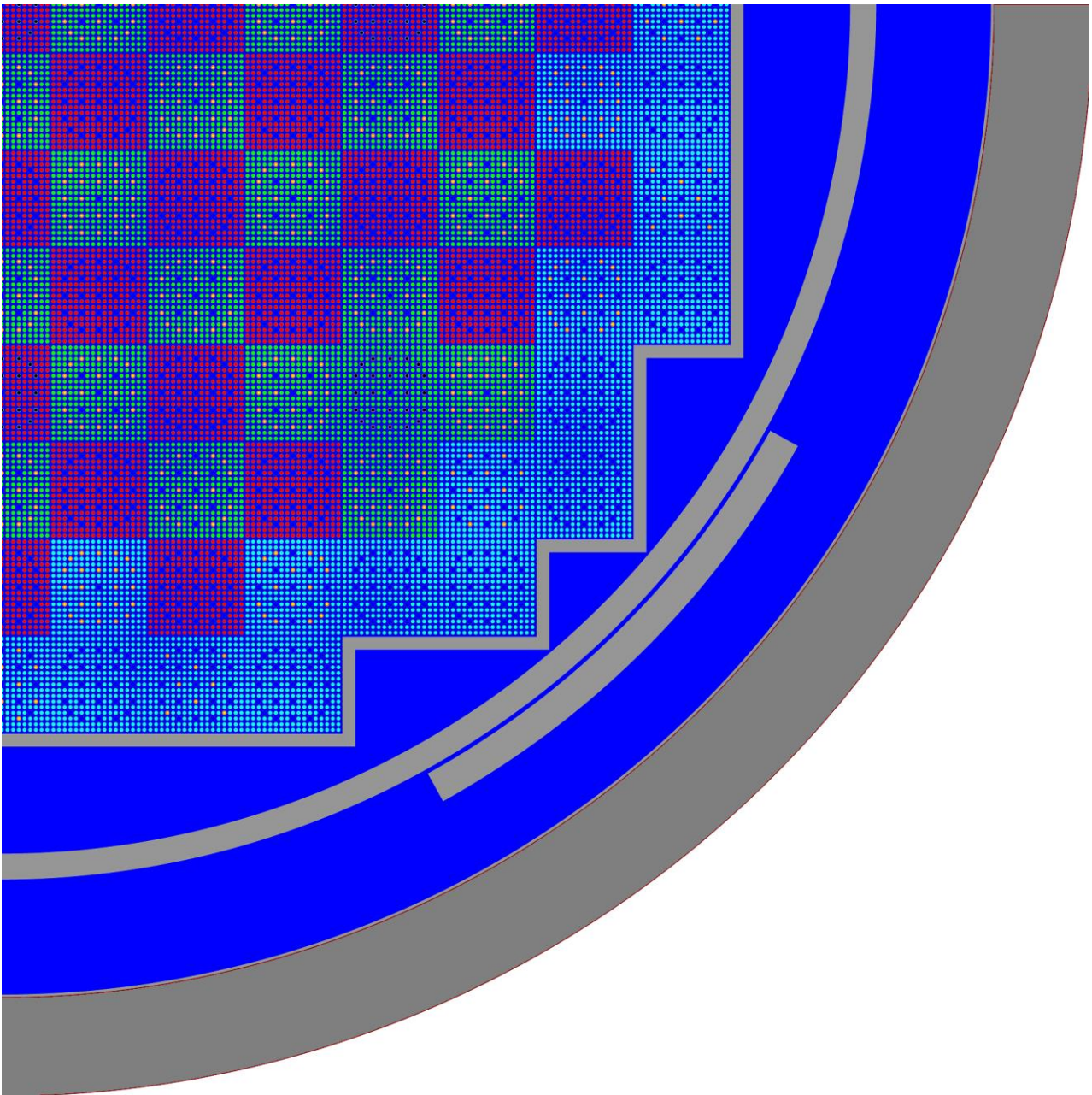
Figure M3-2: Problem 5-2D Reference Solution Geometry

Mixing Table

The following table provides the precise isotopic number densities used for each mixture in the reference problems.

Table M3-4: Reference Mixing Table

Material	Isotope ID	Atom Density (/barn-cm)
2.11% Fuel	8016	4.57591E-02
	92234	4.04814E-06
	92235	4.88801E-04
	92236	2.23756E-06
	92238	2.23844E-02
2.619% Fuel	8016	4.57617E-02
	92234	5.09503E-06
	92235	6.06709E-04
	92236	2.76809E-06
	92238	2.22663E-02
3.10% Fuel	8016	4.57642E-02
	92234	6.11864E-06
	92235	7.18132E-04
	92236	3.29861E-06
	92238	2.21546E-02
Gap	2004	2.68714E-05
Cladding	24050	3.30121E-06
	24052	6.36606E-05
	24053	7.21860E-06
	24054	1.79686E-06
	26054	8.68307E-06
	26056	1.36306E-04
	26057	3.14789E-06
	26058	4.18926E-07
	40090	2.18865E-02
	40091	4.77292E-03
	40092	7.29551E-03
	40094	7.39335E-03
	40096	1.19110E-03
	50112	4.68066E-06
	50114	3.18478E-06
	50115	1.64064E-06
	50116	7.01616E-05
	50117	3.70592E-05
	50118	1.16872E-04
	50119	4.14504E-05
	50120	1.57212E-04
	50122	2.23417E-05
	50124	2.79392E-05
	72174	3.54138E-09
	72176	1.16423E-07
	72177	4.11686E-07
	72178	6.03806E-07
	72179	3.01460E-07
	72180	7.76449E-07

Material	Isotope ID	Atom Density (/barn-cm)
Moderator 0.743 g/cc	8016	2.48112E-02
	1001	4.96224E-02
	5010	1.07070E-05
	5011	4.30971E-05
Pyrex	5010	9.63266E-04
	5011	3.90172E-03
	8016	4.67761E-02
	14028	1.81980E-02
	14029	9.24474E-04
	14030	6.10133E-04
SS304	6000	3.20895E-04
	14028	1.58197E-03
	14029	8.03653E-05
	14030	5.30394E-05
	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
CS508	6000	3.93598E-03
	26054	4.89841E-03
	26056	7.68945E-02
	26057	1.77583E-03
	26058	2.36330E-04
AIC	47107	2.36159E-02
	47109	2.19403E-02
	48106	3.41523E-05
	48108	2.43165E-05
	48110	3.41250E-04
	48111	3.49720E-04
	48112	6.59276E-04
	48113	3.33873E-04
	48114	7.84957E-04
	48116	2.04641E-04
	49113	3.44262E-04
	49115	7.68050E-03
B4C	5010	1.52689E-02
	5011	6.14591E-02
	6000	1.91820E-02

Input Files

The CE KENO-VI input files for this problem are unreasonably large to be included in this document. They are located on cpile2.ornl.gov in location **/home/agm/vera/**.

Computer Code

The reference calculations were executed with SCALE 6.2 Beta 2 on the Fission supercomputer at Idaho National Laboratory. The approximate run time for the initial case was 6 days on 300 cores, utilizing up to 4 GB of memory per core.

REFERENCE SOLUTION RESULTS

Three cases were executed, including uncontrolled, AIC, and B4C controlled cases, and the eigenvalues, pin powers, assembly powers, and control rod reactivity worths are provided below. The presented results are based on ENFDF/B-VII cross sections. The control rod reactivity worth calculation is done as:

$$\rho_{CRD} = \left(\frac{1}{k_{UNC}} - \frac{1}{k_{CON}} \right) \times 10^5 \ [pcm]$$

Also, note that the reference KENO-VI results are calculated for a quadrant, but are collapsed to octant geometry. The symmetric fuel rod powers are averaged, and the symmetric sigmas are averaged and divided by the square root of two, as the estimate of the uncertainty is inversely proportional to the square root of the population size.

The data size for the output pin powers is extremely large. Please contact the author at godfreyat@ornl.gov to obtain the reference pin power results for these problems.

Table M3-5: Problem 5-2D Reference Solution Results

Case	Description	k-effective	Rod Worth (pcm)
5A-2D	Uncontrolled	1.004085 +/- 0.000008	--
5B-2D	AIC Controlled	0.991496 +/- 0.000008	1265 ± 1
5C-2D	B4C Controlled	0.990227 +/- 0.000009	1394 ± 1

Table M3-6: Problem 5-2D Reference Solution Power Statistics

Powers	Quantity	5A-2D	5B-2D	5C-2D
Assembly Powers	Maximum	1.31539	1.30174	1.32912
	Average Uncertainty	0.004%	0.004%	0.004%
	Maximum Uncertainty	0.008%	0.011%	0.012%
Pin Powers	Maximum	1.44402	1.60240	1.62997
	Average Uncertainty	0.060%	0.060%	0.060%
	Maximum Uncertainty	0.139%	0.137%	0.148%
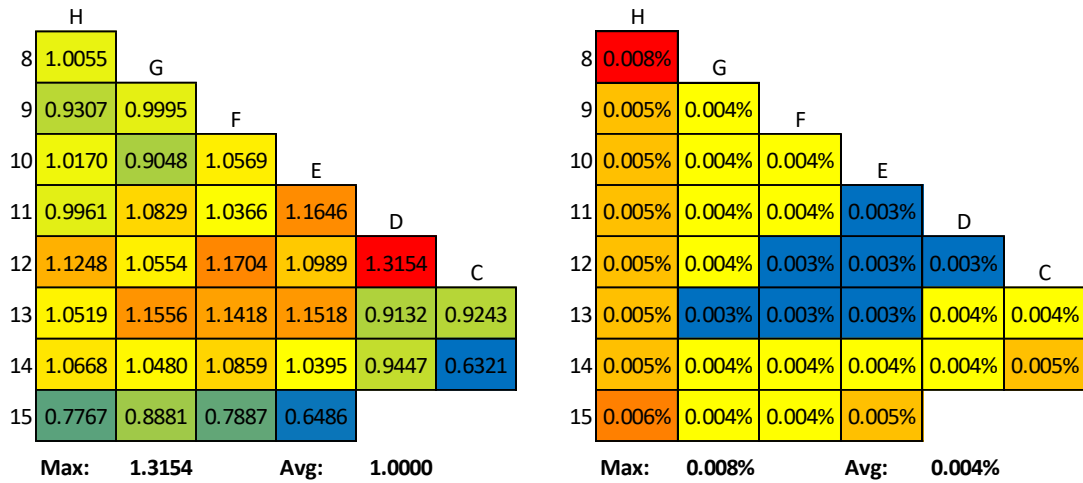
Figure M3-3: Problem 5A-2D Assembly Power and Uncertainty (%) Distribution (Octant)

Assembly Power:

	H	G	F	E	D	C
8	1.0055					
9	0.9307	0.9995				
10	1.0170	0.9048	1.0569			
11	0.9961	1.0829	1.0366	1.1646		
12	1.1248	1.0554	1.1704	1.0989	1.3154	
13	1.0519	1.1556	1.1418	1.1518	0.9132	0.9243
14	1.0668	1.0480	1.0859	1.0395	0.9447	0.6321
15	0.7767	0.8881	0.7887	0.6486		

Max: 1.3154   Avg: 1.0000

Uncertainty (%):

	H	G	F	E	D	C
8	0.008%					
9	0.005%	0.004%				
10	0.005%	0.004%	0.004%			
11	0.005%	0.004%	0.004%	0.003%		
12	0.005%	0.004%	0.003%	0.003%	0.003%	
13	0.005%	0.003%	0.003%	0.003%	0.004%	0.004%
14	0.005%	0.004%	0.004%	0.004%	0.004%	0.005%
15	0.006%	0.004%	0.004%	0.005%		

Max: 0.008%   Avg: 0.004%

Figure M3-4: Problem 5B-2D (AIC) Assembly Power and Uncertainty (%) Distribution (Octant)

Assembly Power:

	H	G	F	E	D	C
8	0.4484					
9	0.7489	0.8853				
10	0.9349	0.8585	1.0418			
11	0.8297	0.9976	1.0146	1.0781		
12	0.5605	0.9425	1.1650	0.9491	0.6242	
13	1.0256	1.2171	1.2400	1.1494	0.7872	0.8528
14	1.2828	1.2658	1.3017	1.1822	0.9922	0.6388
15	1.0002	1.1436	0.9984	0.7930		

Max: 1.3017   Avg: 1.0000

Uncertainty (%):

	H	G	F	E	D	C
8	0.011%					
9	0.006%	0.004%				
10	0.005%	0.004%	0.004%			
11	0.006%	0.004%	0.004%	0.004%		
12	0.007%	0.004%	0.003%	0.004%	0.005%	
13	0.005%	0.003%	0.003%	0.003%	0.004%	0.004%
14	0.005%	0.003%	0.003%	0.003%	0.004%	0.005%
15	0.005%	0.003%	0.004%	0.004%		

Max: 0.011%   Avg: 0.004%

Figure M3-5: Problem 5C-2D (B₄C) Assembly Power and Uncertainty (%) Distribution (Octant)

Assembly Power:

	H	G	F	E	D	C
8	0.3987					
9	0.7247	0.8674				
10	0.9200	0.8484	1.0347			
11	0.8059	0.9833	1.0077	1.0645		
12	0.5068	0.9267	1.1616	0.9295	0.5589	
13	1.0222	1.2244	1.2514	1.1493	0.7727	0.8453
14	1.3106	1.2934	1.3291	1.2003	0.9989	0.6401
15	1.0293	1.1766	1.0254	0.8115		

Max: 1.3291   Avg: 1.0000

Uncertainty (%):

	H	G	F	E	D	C
8	0.012%					
9	0.006%	0.004%				
10	0.005%	0.004%	0.004%			
11	0.006%	0.004%	0.004%	0.004%		
12	0.007%	0.004%	0.003%	0.004%	0.005%	
13	0.005%	0.003%	0.003%	0.003%	0.004%	0.004%
14	0.005%	0.003%	0.003%	0.003%	0.004%	0.005%
15	0.005%	0.003%	0.004%	0.004%		

Max: 0.012%   Avg: 0.004%

Figure M3-6: Problem 5A-2D Pin Power and Uncertainty (%) Distribution
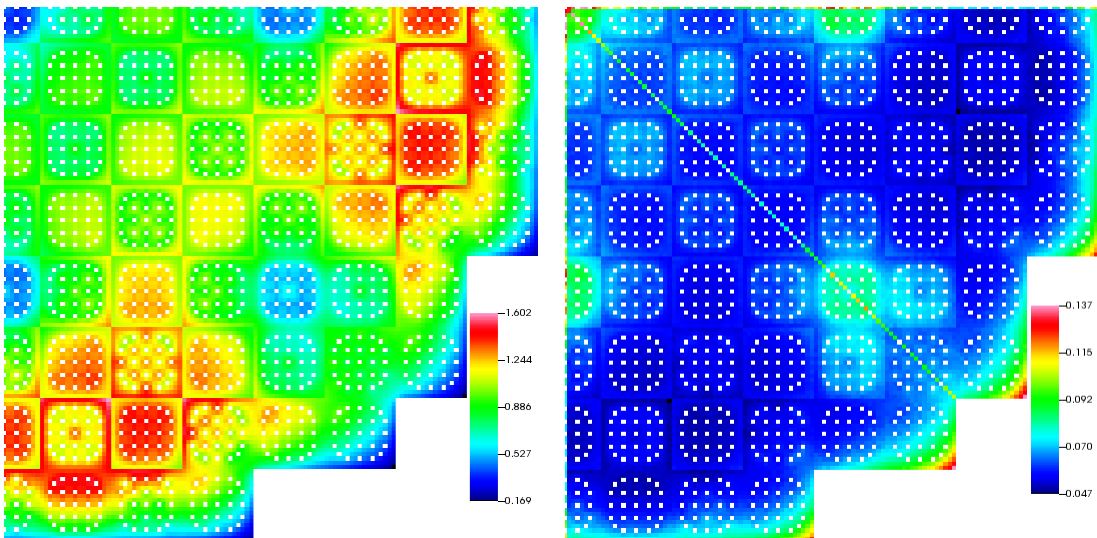
Figure M3-7: Problem 5B-2D (AIC) Pin Power and Uncertainty (%) Distribution
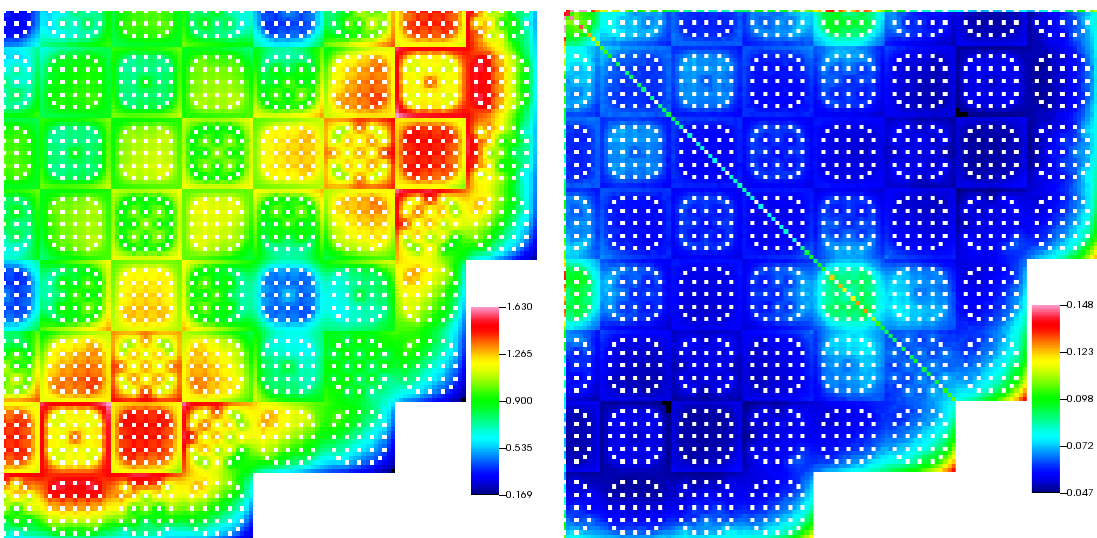
Figure M3-8: Problem 5C-2D (B₄C) Pin Power and Uncertainty (%) Distribution

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APPENDIX A – PROBLEM 1 DATA AND RESULTS

The following are the isotopics and results for Problem 1, in ASCII form.

ENDF/B-VII.0

```
mixture = fuel (3.1%)
  8016  4.57642E-02
 92234  6.11864E-06
 92235  7.18132E-04
 92236  3.29861E-06
 92238  2.21546E-02

mixture = gap
  2004  2.68714E-05

mixture =  cladding (zircaloy-4)
 24050  3.30121E-06
 24052  6.36606E-05
 24053  7.21860E-06
 24054  1.79686E-06
 26054  8.68307E-06
 26056  1.36306E-04
 26057  3.14789E-06
 26058  4.18926E-07
 40090  2.18865E-02
 40091  4.77292E-03
 40092  7.29551E-03
 40094  7.39335E-03
 40096  1.19110E-03
 50112  4.68066E-06
 50114  3.18478E-06
 50115  1.64064E-06
 50116  7.01616E-05
 50117  3.70592E-05
 50118  1.16872E-04
 50119  4.14504E-05
 50120  1.57212E-04
 50122  2.23417E-05
 50124  2.79392E-05
 72174  3.54138E-09
 72176  1.16423E-07
 72177  4.11686E-07
 72178  6.03806E-07
 72179  3.01460E-07
 72180  7.76449E-07

mixture = moderator (1A)
  1001  4.96224E-02
  5010  1.07070E-05
  5011  4.30971E-05
  8016  2.48112E-02

mixture =  moderator (1B-1D)
  1001  4.41459E-02
  5010  9.52537E-06
  5011  3.83408E-05
  8016  2.20729E-02
```

```
mixture = IFBA
  5010  2.16410E-02
  5011  1.96824E-02
 40090  1.06304E-02
 40091  2.31824E-03
 40092  3.54348E-03
 40094  3.59100E-03
 40096  5.78528E-04
```

ENDF/B-VI.8

```
mixture = fuel (3.1%)
  8016  4.57642E-02
 92234  6.11864E-06
 92235  7.18132E-04
 92236  3.29861E-06
 92238  2.21546E-02

mixture = gap
  2004  2.68714E-05

mixture =  cladding (zircaloy-4)
 24050  3.30121E-06
 24052  6.36606E-05
 24053  7.21860E-06
 24054  1.79686E-06
 26054  8.68307E-06
 26056  1.36306E-04
 26057  3.14789E-06
 26058  4.18926E-07
 40000  4.25393E-02
 50112  4.68066E-06
 50114  3.18478E-06
 50115  1.64064E-06
 50116  7.01616E-05
 50117  3.70592E-05
 50118  1.16872E-04
 50119  4.14504E-05
 50120  1.57212E-04
 50122  2.23417E-05
 50124  2.79392E-05
 72000  2.21330E-06

mixture = moderator (1A)
  1001  4.96224E-02
  5010  1.07070E-05
  5011  4.30971E-05
  8016  2.48112E-02

mixture =  moderator (1B-1D)
  1001  4.41459E-02
  5010  9.52537E-06
  5011  3.83408E-05
  8016  2.20729E-02

mixture = IFBA
  5010  2.16410E-02
  5011  1.96824E-02
 40000  2.06617E-02
```

Problem 1 ENDF/B-VII.0 Results

```
Case   k-eff      Sigma
1A   1.187038   0.000054
1B   1.182149   0.000068
1C   1.171722   0.000072
1D   1.162603   0.000071
1E   0.771691   0.000076
```

Case 1A **@ 600K isothermal** = 1.185516 +/- 0.000067

Problem 1 ENDF/B-VI.8 Results

```
Case   k-eff      Sigma
1A   1.183364   0.000111 *temperature adjustment
1B   1.178522   0.000071
1C   1.168114   0.000072
1D   1.159223   0.000071
1E   0.770329   0.000077
```

Case 1A @ **600K isothermal** = 1.181842 +/- 0.000071

Sample CE KENO-VI input for Problem 1

```
=csas6
casl vera benchmark problem #1a
ce_v7_endf
read composition
 uo2     1 den=10.257     1.0     565.0  92234  0.0263
                                         92235  3.1000
                                         92236  0.0143
                                         92238 96.8594 end
 he      2 den=0.0001786 1.0     565.0 end
 zirc4  3 den=6.56       1.0     565.0 end
 h2o     4 den=0.743      0.9987 565.0 end
 boron  4 den=0.743      0.0013 565.0 end
end composition

read parameter
 gen=1100
 npg=100000
 nsk=100
 htm=no
end parameter

read geometry
global unit 1
 com='fuel rod'
 cylinder 1  0.4096  2p0.5
 cylinder 2  0.418   2p0.5
 cylinder 3  0.475   2p0.5
 cuboid   4  4p0.63  2p0.5
 media 1 1 1
 media 2 1 2 -1
 media 3 1 3 -2
 media 4 1 4 -3
 boundary 4

end geometry
read bnds
    body=4
    all=mirror
end bnds
end data
end
```

APPENDIX B – PROBLEM 2 ENDF/B-VII DATA AND RESULTS

This appendix contains the isotopics and results of Problem 2 CE KENO-VI calculations using <u>ENDF/B-VII.0</u> cross sections in ASCII form.

```
mixture = 3.1% fuel          mixture = moderator (2B-
  8016  4.57642E-02          2D)                              mixture = B4C
 92234  6.11864E-06            1001  4.41459E-02                5010  1.52689E-02
 92235  7.18132E-04            8016  2.20729E-02                5011  6.14591E-02
 92236  3.29861E-06            5010  9.52537E-06                6000  1.91820E-02
 92238  2.21546E-02            5011  3.83408E-05
                                                              mixture = 3.6% fuel (2K)
mixture = gaps and           Mixture = pyrex                    8016  4.57669E-02
plenums                        5010  9.63266E-04              92234  7.21203E-06
  2004  2.68714E-05            5011  3.90172E-03              92235  8.33952E-04
                               8016  4.67761E-02              92236  3.82913E-06
mixture = Zircaloy-4          14028  1.81980E-02              92238  2.20384E-02
(clad, tubes, WABA, grid)     14029  9.24474E-04
 24050  3.30121E-06           14030  6.10133E-04              mixture = ifba (2L-2N)
 24052  6.36606E-05                                             5010  2.16410E-02
 24053  7.21860E-06          mixture = stainless steel         5011  1.96824E-02
 24054  1.79686E-06            6000  3.20895E-04              40090  1.06304E-02
 26054  8.68307E-06           14028  1.58197E-03              40091  2.31824E-03
 26056  1.36306E-04           14029  8.03653E-05              40092  3.54348E-03
 26057  3.14789E-06           14030  5.30394E-05              40094  3.59100E-03
 26058  4.18926E-07           15031  6.99938E-05              40096  5.78528E-04
 40090  2.18865E-02           24050  7.64915E-04
 40091  4.77292E-03           24052  1.47506E-02              mixture = waba
 40092  7.29551E-03           24053  1.67260E-03                5010  2.98553E-03
 40094  7.39335E-03           24054  4.16346E-04                5011  1.21192E-02
 40096  1.19110E-03           25055  1.75387E-03                6000  3.77001E-03
 50112  4.68066E-06           26054  3.44776E-03                8016  5.85563E-02
 50114  3.18478E-06           26056  5.41225E-02              13027  3.90223E-02
 50115  1.64064E-06           26057  1.24992E-03
 50116  7.01616E-05           26058  1.66342E-04              mixture = gadolinia
 50117  3.70592E-05           28058  5.30854E-03              (2O,2P)
 50118  1.16872E-04           28060  2.04484E-03                8016  4.53705E-02
 50119  4.14504E-05           28061  8.88879E-05              64152  3.35960E-06
 50120  1.57212E-04           28062  2.83413E-04              64154  3.66190E-05
 50122  2.23417E-05           28064  7.21770E-05              64155  2.48606E-04
 50124  2.79392E-05                                           64156  3.43849E-04
 72174  3.54138E-09          mixture = AIC                    64157  2.62884E-04
 72176  1.16423E-07           47107  2.36159E-02              64158  4.17255E-04
 72177  4.11686E-07           47109  2.19403E-02              64160  3.67198E-04
 72178  6.03806E-07           48106  3.41523E-05              92234  3.18096E-06
 72179  3.01460E-07           48108  2.43165E-05              92235  3.90500E-04
 72180  7.76449E-07           48110  3.41250E-04              92236  1.79300E-06
                              48111  3.49720E-04              92238  2.10299E-02
mixture = moderator          48112  6.59276E-04
(2A,2E-2P)                    48113  3.33873E-04
  1001  4.96224E-02           48114  7.84957E-04
  8016  2.48112E-02           48116  2.04641E-04
  5010  1.07070E-05           49113  3.44262E-04
  5011  4.30971E-05           49115  7.68050E-03
```

```
Case   k-eff      Sigma
2A   1.182175  0.000017
2B   1.183360  0.000024
2C   1.173751  0.000023
2D   1.165591  0.000023
2E   1.069627  0.000024
2F   0.976018  0.000026
2G   0.847695  0.000025
2H   0.788221  0.000025
2I   1.179916  0.000024
2J   0.975193  0.000025
2K   1.020063  0.000025
2L   1.018915  0.000024
2M   0.938796  0.000025
2N   0.869615  0.000025
2O   1.047729  0.000024
2P   0.927410  0.000024
2Q   1.171940  0.000016
```

Case 2A **@ 600K isothermal** = 1.180818 +/- 0.000024

```
2A Pin Powers
------------------------------------
0.00000
1.03638  1.00894
1.03711  1.00930  1.01038
0.00000  1.03675  1.03855  0.00000
1.03530  1.00894  1.01183  1.04505  1.03133
1.03277  1.00533  1.00894  1.04577  1.05155  0.00000
0.00000  1.02663  1.02808  0.00000  1.03602  1.01797  0.97355
1.01219  0.98800  0.98800  1.01147  0.98366  0.96488  0.94827  0.93888
0.97644  0.97211  0.97138  0.97391  0.96452  0.95513  0.94575  0.94177  0.94755
```

```
2A Pin Power Uncertainties
------------------------------------
0.000%
0.027%  0.028%
0.027%  0.018%  0.028%
0.000%  0.019%  0.019%  0.000%
0.027%  0.019%  0.019%  0.018%  0.027%
0.027%  0.020%  0.019%  0.019%  0.020%  0.000%
0.000%  0.019%  0.019%  0.000%  0.019%  0.019%  0.027%
0.028%  0.019%  0.019%  0.019%  0.019%  0.020%  0.020%  0.028%
0.027%  0.020%  0.020%  0.020%  0.019%  0.020%  0.020%  0.019%  0.028%
```

```
2B Pin Powers
------------------------------------
0.00000
1.03552  1.01134
1.03624  1.01134  1.01206
0.00000  1.03588  1.03732  0.00000
1.03371  1.00989  1.01242  1.04238  1.03083
1.03083  1.00664  1.00953  1.04274  1.04743  0.00000
0.00000  1.02433  1.02577  0.00000  1.03263  1.01459  0.97452
1.01025  0.98932  0.98932  1.00989  0.98391  0.96658  0.95034  0.94059
0.97813  0.97416  0.97380  0.97524  0.96622  0.95647  0.94745  0.94348  0.94781
```

```
2B Pin Power Uncertainties
------------------------------------
0.000%
0.027%  0.027%
0.026%  0.019%  0.026%
0.000%  0.019%  0.018%  0.000%
0.027%  0.020%  0.019%  0.019%  0.027%
0.027%  0.019%  0.019%  0.018%  0.019%  0.000%
0.000%  0.019%  0.019%  0.000%  0.019%  0.019%  0.028%
0.027%  0.019%  0.019%  0.019%  0.019%  0.019%  0.020%  0.027%
0.028%  0.019%  0.020%  0.019%  0.020%  0.019%  0.020%  0.019%  0.027%
```

```
2C Pin Powers
-----------------------------------
0.00000
1.03569  1.01094
1.03642  1.01131  1.01240
0.00000  1.03642  1.03751  0.00000
1.03460  1.01022  1.01240  1.04224  1.03060
1.03060  1.00658  1.00949  1.04261  1.04734  0.00000
0.00000  1.02477  1.02587  0.00000  1.03242  1.01495  0.97383
1.01022  0.98911  0.98911  1.01022  0.98402  0.96655  0.94944  0.94107
0.97819  0.97419  0.97383  0.97528  0.96582  0.95636  0.94762  0.94326  0.94762

2C Pin Power Uncertainties
-----------------------------------
0.000%
0.027%  0.027%
0.027%  0.019%  0.028%
0.000%  0.019%  0.018%  0.000%
0.027%  0.019%  0.019%  0.018%  0.026%
0.027%  0.019%  0.019%  0.019%  0.019%  0.000%
0.000%  0.019%  0.019%  0.000%  0.019%  0.019%  0.028%
0.027%  0.019%  0.019%  0.019%  0.019%  0.020%  0.019%  0.027%
0.027%  0.019%  0.019%  0.019%  0.020%  0.020%  0.020%  0.019%  0.028%

2D Pin Powers
-----------------------------------
0.00000
1.03604  1.01148
1.03640  1.01185  1.01222
0.00000  1.03640  1.03787  0.00000
1.03420  1.01002  1.01222  1.04263  1.03127
1.03054  1.00672  1.00965  1.04190  1.04740  0.00000
0.00000  1.02431  1.02578  0.00000  1.03274  1.01478  0.97410
1.01112  0.98949  0.98913  1.01002  0.98363  0.96567  0.94991  0.94039
0.97850  0.97410  0.97374  0.97520  0.96641  0.95651  0.94735  0.94258  0.94772

2D Pin Power Uncertainties
-----------------------------------
0.000%
0.027%  0.027%
0.027%  0.019%  0.027%
0.000%  0.019%  0.019%  0.000%
0.027%  0.019%  0.019%  0.019%  0.027%
0.026%  0.020%  0.019%  0.019%  0.019%  0.000%
0.000%  0.019%  0.019%  0.000%  0.019%  0.019%  0.027%
0.027%  0.019%  0.019%  0.019%  0.019%  0.019%  0.019%  0.028%
0.028%  0.019%  0.020%  0.020%  0.019%  0.019%  0.019%  0.019%  0.028%

2E Pin Powers
-----------------------------------
0.00000
1.01701  0.99304
0.92993  0.96348  0.99624
0.00000  0.93312  1.02500  0.00000
0.93472  0.96947  1.00223  1.03618  1.02899
1.02899  1.00343  0.97506  0.95230  1.02260  0.00000
0.00000  1.03498  0.94191  0.00000  0.95789  1.04257  1.03139
1.05775  1.02220  0.97626  0.93552  0.97866  1.01461  1.02460  1.02899
1.03458  1.02380  1.00542  0.99384  1.00542  1.02180  1.03139  1.03978  1.05136

2E Pin Power Uncertainties
-----------------------------------
0.000%
0.029%  0.029%
0.029%  0.021%  0.027%
0.000%  0.021%  0.020%  0.000%
0.029%  0.020%  0.020%  0.019%  0.027%
0.029%  0.020%  0.020%  0.021%  0.020%  0.000%
0.000%  0.020%  0.020%  0.000%  0.021%  0.019%  0.028%
0.028%  0.020%  0.020%  0.021%  0.020%  0.019%  0.020%  0.028%
0.028%  0.020%  0.021%  0.020%  0.020%  0.020%  0.020%  0.020%  0.028%
```

```
2F Pin Powers
-----------------------------------
0.00000
1.07828  1.04279
0.97137  0.99065  0.97356
0.00000  0.93325  0.92624  0.00000
0.92580  0.95910  0.95428  0.91178  0.92624
0.92799  0.96173  0.95866  0.91266  0.90696  0.00000
0.00000  0.94201  0.94114  0.00000  0.93500  0.96699  1.03402
0.97443  1.00467  1.00598  0.97925  1.01913  1.05023  1.08309  1.10938
1.04717  1.05286  1.05505  1.05505  1.07170  1.09230  1.11377  1.13392  1.15407

2F Pin Power Uncertainties
-----------------------------------
0.000%
0.029%  0.029%
0.030%  0.022%  0.030%
0.000%  0.022%  0.022%  0.000%
0.031%  0.022%  0.022%  0.022%  0.030%
0.030%  0.021%  0.022%  0.022%  0.022%  0.000%
0.000%  0.023%  0.022%  0.000%  0.021%  0.022%  0.029%
0.030%  0.021%  0.022%  0.021%  0.021%  0.020%  0.020%  0.029%
0.029%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.019%  0.028%

2G Pin Powers
-----------------------------------
0.00000
1.07318  1.03531
0.93925  0.96602  0.94107
0.00000  0.88546  0.87622  0.00000
0.87355  0.91996  0.91380  0.85294  0.87188
0.87839  0.92733  0.92117  0.85592  0.85072  0.00000
0.00000  0.90829  0.90718  0.00000  0.90698  0.96460  1.07066
0.96455  1.00576  1.00975  0.97783  1.03935  1.09439  1.15247  1.19994
1.07066  1.08025  1.08581  1.08985  1.12015  1.15853  1.20045  1.23631  1.26661

2G Pin Power Uncertainties
-----------------------------------
0.000%
0.030%  0.031%
0.033%  0.022%  0.032%
0.000%  0.024%  0.024%  0.000%
0.034%  0.023%  0.023%  0.024%  0.034%
0.034%  0.023%  0.023%  0.024%  0.024%  0.000%
0.000%  0.023%  0.023%  0.000%  0.023%  0.023%  0.030%
0.032%  0.022%  0.023%  0.022%  0.022%  0.021%  0.021%  0.028%
0.031%  0.022%  0.022%  0.022%  0.021%  0.021%  0.021%  0.020%  0.029%

2H Pin Powers
-----------------------------------
0.00000
1.06065  1.02146
0.92214  0.94813  0.92100
0.00000  0.86463  0.85468  0.00000
0.85158  0.90007  0.89311  0.83114  0.85109
0.85886  0.90926  0.90317  0.83614  0.83435  0.00000
0.00000  0.89523  0.89616  0.00000  0.90224  0.97074  1.09050
0.96085  1.00412  1.01042  0.98020  1.04951  1.11442  1.18400  1.24163
1.07511  1.08615  1.09430  1.10192  1.14051  1.18726  1.23836  1.28294  1.31882

2H Pin Power Uncertainties
-----------------------------------
0.000%
0.033%  0.032%
0.034%  0.024%  0.034%
0.000%  0.025%  0.025%  0.000%
0.036%  0.024%  0.025%  0.025%  0.036%
0.035%  0.025%  0.024%  0.025%  0.025%  0.000%
0.000%  0.025%  0.025%  0.000%  0.024%  0.024%  0.032%
0.033%  0.023%  0.023%  0.023%  0.022%  0.022%  0.021%  0.030%
0.032%  0.022%  0.022%  0.022%  0.022%  0.022%  0.021%  0.021%  0.029%
```

```
2I Pin Powers
-----------------------------------
0.00000
1.00445  0.99287
1.02507  1.00228  1.00734
0.00000  1.03339  1.03665  0.00000
1.03520  1.00879  1.01168  1.04497  1.03267
1.03267  1.00698  1.01024  1.04570  1.05148  0.00000
0.00000  1.02688  1.02869  0.00000  1.03701  1.01892  0.97550
1.01277  0.98997  0.99033  1.01277  0.98563  0.96790  0.95126  0.94149
0.97912  0.97478  0.97478  0.97586  0.96790  0.95741  0.94872  0.94438  0.95017

2I Pin Power Uncertainties
-----------------------------------
0.000%
0.028%  0.027%
0.027%  0.019%  0.027%
0.000%  0.019%  0.019%  0.000%
0.027%  0.020%  0.019%  0.019%  0.027%
0.027%  0.019%  0.019%  0.019%  0.019%  0.000%
0.000%  0.018%  0.019%  0.000%  0.019%  0.019%  0.028%
0.028%  0.019%  0.019%  0.020%  0.019%  0.019%  0.020%  0.028%
0.028%  0.019%  0.020%  0.020%  0.020%  0.020%  0.020%  0.019%  0.029%

2J Pin Powers
-----------------------------------
0.00000
1.04149  1.02263
0.95904  0.98229  0.96825
0.00000  0.93054  0.92484  0.00000
0.92616  0.95904  0.95554  0.91300  0.92879
0.92879  0.96299  0.95948  0.91432  0.90861  0.00000
0.00000  0.94282  0.94282  0.00000  0.93712  0.96957  1.03579
0.97615  1.00597  1.00772  0.98053  1.02131  1.05289  1.08490  1.11209
1.04894  1.05552  1.05771  1.05771  1.07438  1.09411  1.11604  1.13621  1.15594

2J Pin Power Uncertainties
-----------------------------------
0.000%
0.029%  0.030%
0.031%  0.021%  0.030%
0.000%  0.023%  0.022%  0.000%
0.031%  0.021%  0.021%  0.022%  0.030%
0.031%  0.022%  0.022%  0.022%  0.022%  0.000%
0.000%  0.022%  0.021%  0.000%  0.022%  0.022%  0.029%
0.030%  0.021%  0.021%  0.021%  0.021%  0.021%  0.020%  0.028%
0.028%  0.021%  0.021%  0.021%  0.021%  0.020%  0.021%  0.020%  0.029%

2K Pin Powers
-----------------------------------
0.00000
0.97653  1.06370
0.98994  1.00545  0.98491
0.00000  0.94552  0.93881  0.00000
0.93797  0.96899  0.96438  0.92372  0.93881
0.93881  0.97066  0.96731  0.92456  0.91953  0.00000
0.00000  0.95096  0.95054  0.00000  0.94761  0.98072  1.04946
0.98114  1.01048  1.01215  0.98743  1.02850  1.06454  1.10729  1.01593
1.05239  1.05784  1.06077  1.06203  1.08131  1.10981  1.01467  1.04526  1.06873

2K Pin Power Uncertainties
-----------------------------------
0.000%
0.029%  0.029%
0.029%  0.021%  0.029%
0.000%  0.021%  0.022%  0.000%
0.031%  0.021%  0.021%  0.022%  0.031%
0.030%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.022%  0.029%
0.030%  0.021%  0.021%  0.021%  0.020%  0.020%  0.019%  0.029%
0.028%  0.020%  0.020%  0.020%  0.020%  0.021%  0.021%  0.020%  0.029%
```

```
2L Pin Powers
-----------------------------------
0.00000
0.94806  0.99672
1.03280  1.00008  0.93128
0.00000  0.95561  1.02860  0.00000
0.96064  1.00931  1.01056  0.94093  0.98162
1.04748  1.02189  1.01602  0.94051  0.93883  0.00000
0.00000  0.96903  1.04664  0.00000  0.95435  1.03322  0.93883
0.96442  1.01979  1.02734  0.96484  1.01518  1.02231  1.00931  1.00763
1.03112  1.03615  1.03825  1.03070  1.03406  1.03531  1.02567  1.00259  0.90527

2L Pin Power Uncertainties
-----------------------------------
0.000%
0.031%  0.029%
0.029%  0.021%  0.031%
0.000%  0.022%  0.021%  0.000%
0.030%  0.021%  0.021%  0.021%  0.029%
0.029%  0.021%  0.021%  0.021%  0.022%  0.000%
0.000%  0.022%  0.021%  0.000%  0.021%  0.021%  0.029%
0.031%  0.021%  0.021%  0.021%  0.021%  0.020%  0.021%  0.028%
0.029%  0.021%  0.021%  0.021%  0.020%  0.021%  0.021%  0.021%  0.029%

2M Pin Powers
-----------------------------------
0.00000
0.98326  1.03885
0.98463  1.03930  1.03885
0.00000  0.98326  0.98235  0.00000
0.98280  1.03702  1.03611  0.97597  1.02062
0.98144  1.03611  1.03429  0.97141  0.96959  0.00000
0.00000  0.97688  0.97779  0.00000  0.96959  0.96594  1.00422
0.97278  1.01925  1.02973  0.97916  1.01698  1.01698  0.94407  1.01515
1.00786  0.94316  1.03338  1.02882  0.94726  1.03247  1.03611  1.03064  0.94225

2M Pin Power Uncertainties
-----------------------------------
0.000%
0.032%  0.030%
0.031%  0.022%  0.030%
0.000%  0.022%  0.022%  0.000%
0.031%  0.021%  0.021%  0.021%  0.030%
0.031%  0.022%  0.021%  0.022%  0.022%  0.000%
0.000%  0.022%  0.023%  0.000%  0.021%  0.022%  0.030%
0.032%  0.022%  0.022%  0.022%  0.022%  0.022%  0.022%  0.031%
0.030%  0.022%  0.021%  0.021%  0.022%  0.022%  0.021%  0.021%  0.032%

2N Pin Powers
-----------------------------------
0.00000
0.97563  1.02584
0.89928  0.99630  1.02091
0.00000  0.89229  0.96568  0.00000
0.86974  0.97218  1.00565  0.94683  0.95574
0.86783  0.96440  0.97001  0.86512  0.84671  0.00000
0.00000  0.88190  0.88313  0.00000  0.87053  0.91114  1.05537
0.92473  1.01550  1.01796  0.93177  1.03666  1.08244  1.12724  1.15382
1.07998  1.09278  1.09623  1.09229  1.11838  1.14594  1.16612  1.16022  1.06029

2N Pin Power Uncertainties
-----------------------------------
0.000%
0.032%  0.032%
0.034%  0.022%  0.032%
0.000%  0.024%  0.023%  0.000%
0.034%  0.023%  0.023%  0.023%  0.034%
0.034%  0.023%  0.023%  0.023%  0.024%  0.000%
0.000%  0.024%  0.023%  0.000%  0.023%  0.023%  0.031%
0.033%  0.023%  0.022%  0.023%  0.022%  0.022%  0.021%  0.029%
0.031%  0.022%  0.022%  0.021%  0.022%  0.021%  0.021%  0.022%  0.031%
```

```
2O Pin Powers
-----------------------------------
0.00000
1.10485  1.07100
1.08894  1.05020  1.01798
0.00000  1.04082  0.98046  0.00000
1.04775  0.96577  0.21754  0.98821  1.03674
1.07263  1.02246  0.97719  1.05550  1.08119  0.00000
0.00000  1.09261  1.08242  0.00000  1.07875  0.99310  0.21730
1.10526  1.07793  1.07222  1.09180  1.04775  0.99310  0.92540  0.96414
1.07712  1.07141  1.06774  1.06366  1.04286  1.01675  0.99351  0.99963  1.01635

2O Pin Power Uncertainties
-----------------------------------
0.000%
0.027%  0.027%
0.028%  0.021%  0.030%
0.000%  0.020%  0.021%  0.000%
0.028%  0.021%  0.038%  0.021%  0.028%
0.028%  0.021%  0.021%  0.021%  0.020%  0.000%
0.000%  0.020%  0.021%  0.000%  0.020%  0.021%  0.055%
0.028%  0.019%  0.020%  0.020%  0.019%  0.021%  0.022%  0.029%
0.028%  0.020%  0.020%  0.020%  0.020%  0.020%  0.021%  0.021%  0.028%

2P Pin Powers
-----------------------------------
0.00000
1.16877  1.11158
1.14110  1.05300  0.24418
0.00000  1.11803  1.06361  0.00000
1.06591  1.08206  1.08805  1.06269  0.24427
0.24588  1.04008  1.09497  1.10881  1.06084  0.00000
0.00000  1.11480  1.10696  0.00000  1.08067  1.03778  0.24307
1.14755  1.10881  1.03317  0.24399  1.00780  1.04055  1.00503  1.06084
1.13372  1.11434  1.06407  0.99535  1.04377  1.07514  1.08206  1.10512  1.13003

2P Pin Power Uncertainties
-----------------------------------
0.000%
0.029%  0.030%
0.029%  0.021%  0.052%
0.000%  0.020%  0.022%  0.000%
0.031%  0.021%  0.021%  0.022%  0.055%
0.054%  0.021%  0.020%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.022%  0.053%
0.029%  0.021%  0.022%  0.038%  0.022%  0.022%  0.022%  0.030%
0.029%  0.021%  0.021%  0.022%  0.021%  0.021%  0.021%  0.021%  0.029%

2Q Pin Powers
-----------------------------------
0.00000
1.03675  1.01053
1.03712  1.01125  1.01198
0.00000  1.03748  1.03894  0.00000
1.03530  1.00980  1.01235  1.04477  1.03311
1.03202  1.00688  1.00980  1.04477  1.05133  0.00000
0.00000  1.02583  1.02728  0.00000  1.03566  1.01599  0.97264
1.01125  0.98830  0.98794  1.01089  0.98284  0.96390  0.94678  0.93694
0.97738  0.97264  0.97228  0.97446  0.96463  0.95479  0.94568  0.94131  0.94787

2Q Pin Power Uncertainties
-----------------------------------
0.000%
0.026%  0.027%
0.027%  0.019%  0.026%
0.000%  0.019%  0.019%  0.000%
0.027%  0.019%  0.019%  0.019%  0.027%
0.027%  0.019%  0.019%  0.019%  0.018%  0.000%
0.000%  0.019%  0.019%  0.000%  0.019%  0.019%  0.027%
0.027%  0.020%  0.019%  0.018%  0.019%  0.019%  0.019%  0.027%
0.027%  0.019%  0.019%  0.019%  0.019%  0.020%  0.019%  0.020%  0.027%
```

```
2A @ 600K Pin Powers
------------------------------------
0.00000
1.03553  1.00950
1.03553  1.01022  1.01095
0.00000  1.03626  1.03842  0.00000
1.03481  1.00914  1.01167  1.04457  1.03192
1.03156  1.00625  1.00878  1.04457  1.05000  0.00000
0.00000  1.02505  1.02722  0.00000  1.03517  1.01673  0.97407
1.01095  0.98853  0.98853  1.01095  0.98347  0.96611  0.94876  0.93936
0.97732  0.97298  0.97226  0.97443  0.96539  0.95563  0.94695  0.94261  0.94731

2A @ 600K Pin Uncertainties – not an official problem
------------------------------------
0.000%
0.027%  0.028%
0.025%  0.019%  0.027%
0.000%  0.019%  0.019%  0.000%
0.027%  0.019%  0.020%  0.019%  0.028%
0.028%  0.019%  0.019%  0.019%  0.019%  0.000%
0.000%  0.019%  0.019%  0.000%  0.019%  0.019%  0.027%
0.027%  0.020%  0.019%  0.019%  0.020%  0.019%  0.020%  0.029%
0.028%  0.019%  0.020%  0.019%  0.020%  0.020%  0.019%  0.020%  0.028%
```

APPENDIX C – PROBLEM 2 ENDF/B-VI DATA AND RESULTS

This appendix contains the isotopics and results of Problem 2 CE KENO-VI calculations using <u>ENDF/B-VI.8</u> cross sections in ASCII form.

```
mixture = 3.1% fuel
  8016   4.57642E-02          Mixture = pyrex
 92234   6.11864E-06            5011   3.90172E-03
 92235   7.18132E-04            5010   9.63266E-04
 92236   3.29861E-06            8016   4.67761E-02
 92238   2.21546E-02           14000   1.97326E-02

mixture = gaps and
plenums                       mixture = stainless
  2004   2.68714E-05          steel
                               6000   3.20895E-04
mixture = Zircaloy-4          14000   1.71537E-03
(clad, tubes, WABA)           15031   6.99938E-05
 24050   3.30121E-06          24050   7.64915E-04
 24052   6.36606E-05          24052   1.47506E-02
 24053   7.21860E-06          24053   1.67260E-03
 24054   1.79686E-06          24054   4.16346E-04
 26054   8.68307E-06          25055   1.75387E-03
 26056   1.36306E-04          26054   3.44776E-03
 26057   3.14789E-06          26056   5.41225E-02
 26058   4.18926E-07          26057   1.24992E-03
 40000   4.25393E-02          26058   1.66342E-04
 50112   4.68066E-06          28058   5.30854E-03
 50114   3.18478E-06          28060   2.04484E-03
 50115   1.64064E-06          28061   8.88879E-05
 50116   7.01616E-05          28062   2.83413E-04
 50117   3.70592E-05          28064   7.21770E-05
 50118   1.16872E-04
 50119   4.14504E-05          mixture = AIC
 50120   1.57212E-04          47107   2.36159E-02
 50122   2.23417E-05          47109   2.19403E-02
 50124   2.79392E-05          48000   2.73220E-03
 72000   2.21330E-06          49000   8.02477E-03

mixture = moderator
(2A,2E-2P)                    mixture = B4C
  1001   4.96224E-02            5010   1.52689E-02
  8016   2.48112E-02            5011   6.14591E-02
  5010   1.07070E-05            6000   1.91820E-02
  5011   4.30971E-05
                              mixture = 3.6% fuel (2K)
                                8016   4.57669E-02
mixture = moderator (2B-       92234   7.21203E-06
2D)                            92235   8.33952E-04
  1001   4.41459E-02          92236   3.82913E-06
  8016   2.20729E-02          92238   2.20384E-02
  5010   9.52537E-06
  5011   3.83408E-05
```

```
mixture = ifba (2L-2N)
  5010   2.16410E-02
  5011   1.96824E-02
 40000   2.06617E-02

mixture = waba
  5010   2.98553E-03
  5011   1.21192E-02
  6000   3.77001E-03
  8016   5.85563E-02
 13027   3.90223E-02

mixture = gadolinia
(2O,2P)
  8016   4.53705E-02
 64152   3.35960E-06
 64154   3.66190E-05
 64155   2.48606E-04
 64156   3.43849E-04
 64157   2.62884E-04
 64158   4.17255E-04
 64160   3.67198E-04
 92234   3.18096E-06
 92235   3.90500E-04
 92236   1.79300E-06
 92238   2.10299E-02
```

```
Case  k-eff     Sigma
2A  1.178520  0.000037 *temperature adjustment
2B  1.179769  0.000021
2C  1.170310  0.000023
2D  1.162145  0.000023
2E  1.066596  0.000025
2F  0.973376  0.000027
2G  0.845626  0.000025
2H  0.785666  0.000024
2I  1.176366  0.000024
2J  0.972619  0.000024
2K  1.017346  0.000024
2L  1.016060  0.000024
2M  0.936422  0.000024
2N  0.867725  0.000024
2O  1.045747  0.000026
2P  0.926637  0.000025


Case 2A @ 600K isothermal = 1.177163 +/- 0.000022
Case 2G @ 300K isothermal = 0.878097 +/- 0.000024
Case 2H @ 300K isothermal = 0.813399 +/- 0.000024


2A Pin Powers *temperature adjustment
----------------------------------
0.00000
1.03658 1.00862
1.03658 1.00971 1.00936
0.00000 1.03768 1.03948 0.00000
1.03585 1.00790 1.01116 1.04638 1.03258
1.03295 1.00609 1.00900 1.04493 1.05184 0.00000
0.00000 1.02605 1.02823 0.00000 1.03695 1.01734 0.97377
1.01154 0.98793 0.98829 1.01190 0.98285 0.96506 0.94835 0.93892
0.97595 0.97159 0.97123 0.97341 0.96434 0.95417 0.94582 0.94182 0.94836


2A Pin Uncertainties
----------------------------------
0.000%
0.034% 0.041%
0.034% 0.029% 0.041%
0.000% 0.029% 0.029% 0.000%
0.034% 0.029% 0.029% 0.029% 0.041%
0.034% 0.029% 0.029% 0.029% 0.029% 0.000%
0.000% 0.029% 0.029% 0.000% 0.029% 0.029% 0.041%
0.034% 0.029% 0.029% 0.029% 0.029% 0.029% 0.029% 0.041%
0.036% 0.029% 0.029% 0.029% 0.029% 0.029% 0.029% 0.029% 0.041%


2B Pin Powers
----------------------------------
0.00000
1.03660 1.01157
1.03660 1.01157 1.01229
0.00000 1.03696 1.03769 0.00000
1.03442 1.00975 1.01229 1.04350 1.03116
1.03152 1.00685 1.00939 1.04277 1.04785 0.00000
0.00000 1.02463 1.02608 0.00000 1.03297 1.01519 0.97383
1.01084 0.98871 0.98943 1.01048 0.98363 0.96585 0.94916 0.93973
0.97819 0.97347 0.97311 0.97528 0.96585 0.95642 0.94662 0.94227 0.94771


2B Pin Uncertainties
----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
```

```
2C Pin Powers
-----------------------------------
0.00000
1.03631 1.01107
1.03668 1.01144 1.01181
0.00000 1.03668 1.03814 0.00000
1.03522 1.00998 1.01181 1.04326 1.03083
1.03192 1.00705 1.00961 1.04290 1.04839 0.00000
0.00000 1.02461 1.02644 0.00000 1.03302 1.01510 0.97376
1.01071 0.98913 0.98913 1.01034 0.98327 0.96571 0.94962 0.94011
0.97779 0.97413 0.97303 0.97486 0.96571 0.95620 0.94669 0.94230 0.94669

2C Pin Uncertainties
-----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%

2D Pin Powers
-----------------------------------
0.00000
1.03630 1.01088
1.03667 1.01162 1.01236
0.00000 1.03704 1.03778 0.00000
1.03409 1.01015 1.01236 1.04367 1.03078
1.03078 1.00646 1.00904 1.04330 1.04809 0.00000
0.00000 1.02525 1.02636 0.00000 1.03299 1.01494 0.97404
1.01088 0.98878 0.98915 1.01015 0.98362 0.96594 0.94899 0.94015
0.97773 0.97368 0.97331 0.97478 0.96557 0.95636 0.94678 0.94273 0.94752

2D Pin Uncertainties
-----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%

2E Pin Powers
-----------------------------------
0.00000
1.01866 0.99257
0.92953 0.96366 0.99658
0.00000 0.93153 1.02549 0.00000
0.93434 0.96888 1.00260 1.03754 1.02870
1.02951 1.00381 0.97530 0.95161 1.02388 0.00000
0.00000 1.03593 0.94157 0.00000 0.95643 1.04316 1.03111
1.05962 1.02228 0.97610 0.93434 0.97851 1.01425 1.02429 1.02951
1.03513 1.02308 1.00541 0.99337 1.00501 1.02148 1.03151 1.04035 1.05199

2E Pin Uncertainties
-----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
```

```
2F Pin Powers
-----------------------------------
0.00000
1.07913 1.04301
0.97078 0.99104 0.97342
0.00000 0.93290 0.92629 0.00000
0.92497 0.95932 0.95448 0.91087 0.92673
0.92761 0.96197 0.95844 0.91175 0.90559 0.00000
0.00000 0.94082 0.94038 0.00000 0.93466 0.96593 1.03332
0.97386 1.00513 1.00601 0.97870 1.01923 1.05050 1.08309 1.11084
1.04918 1.05402 1.05623 1.05623 1.07208 1.09278 1.11393 1.13375 1.15489


2F Pin Uncertainties
-----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%


2G Pin Powers
-----------------------------------
0.00000
1.07635 1.03776
0.93952 0.96623 0.94079
0.00000 0.88428 0.87519 0.00000
0.87195 0.91998 0.91338 0.85189 0.87083
0.87707 0.92652 0.92048 0.85438 0.84874 0.00000
0.00000 0.90688 0.90632 0.00000 0.90530 0.96333 1.07127
0.96374 1.00629 1.00984 0.97699 1.03878 1.09463 1.15352 1.20125
1.07178 1.08143 1.08752 1.09107 1.12204 1.16012 1.20176 1.23780 1.26827


2G Pin Uncertainties
-----------------------------------
0.000%
0.028%  0.030%
0.035%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.035%  0.021%  0.021%  0.021%  0.030%
0.035%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.035%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%


2H Pin Powers
-----------------------------------
0.00000
1.06244 1.02245
0.92189 0.94880 0.92112
0.00000 0.86296 0.85262 0.00000
0.85109 0.89929 0.89218 0.82926 0.84912
0.85760 0.90843 0.90263 0.83435 0.83183 0.00000
0.00000 0.89480 0.89437 0.00000 0.90028 0.96943 1.09083
0.96068 1.00445 1.01019 0.97950 1.04975 1.11556 1.18559 1.24304
1.07716 1.08744 1.09587 1.10298 1.14183 1.18942 1.24140 1.28572 1.32073


2H Pin Uncertainties
-----------------------------------
0.000%
0.028%  0.030%
0.035%  0.021%  0.030%
0.000%  0.028%  0.028%  0.000%
0.035%  0.025%  0.021%  0.028%  0.040%
0.035%  0.021%  0.021%  0.028%  0.028%  0.000%
0.000%  0.025%  0.021%  0.000%  0.021%  0.021%  0.030%
0.035%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.032%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
```

```
2I Pin Powers
-----------------------------------
0.00000
1.00480 0.99280
1.02553 1.00262 1.00662
0.00000 1.03426 1.03753 0.00000
1.03426 1.00881 1.01208 1.04554 1.03281
1.03317 1.00699 1.00953 1.04663 1.05281 0.00000
0.00000 1.02772 1.02917 0.00000 1.03717 1.01935 0.97535
1.01317 0.99026 0.98989 1.01317 0.98517 0.96735 0.95026 0.94044
0.97826 0.97389 0.97389 0.97608 0.96698 0.95716 0.94844 0.94407 0.94916
```

```
2I Pin Uncertainties
-----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
```

```
2J Pin Powers
-----------------------------------
0.00000
1.04213 1.02362
0.95970 0.98306 0.96895
0.00000 0.93016 0.92487 0.00000
0.92531 0.95926 0.95485 0.91209 0.92840
0.92840 0.96278 0.96014 0.91297 0.90724 0.00000
0.00000 0.94295 0.94250 0.00000 0.93633 0.96807 1.03508
0.97557 1.00598 1.00775 0.98042 1.02097 1.05315 1.08489 1.11267
1.05051 1.05580 1.05888 1.05844 1.07520 1.09459 1.11619 1.13691 1.15675
```

```
2J Pin Uncertainties
-----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
```

```
2K Pin Powers
-----------------------------------
0.00000
0.97767 1.06571
0.98946 1.00547 0.98483
0.00000 0.94523 0.93849 0.00000
0.93681 0.96924 0.96503 0.92333 0.93849
0.93849 0.97093 0.96756 0.92417 0.91828 0.00000
0.00000 0.95071 0.95029 0.00000 0.94608 0.97977 1.04970
0.98062 1.01010 1.01221 0.98651 1.02906 1.06486 1.10783 1.01516
1.05349 1.05812 1.06107 1.06234 1.08171 1.11036 1.01558 1.04549 1.06992
```

```
2K Pin Uncertainties
-----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
```

```
2L Pin Powers
----------------------------------
0.00000
0.94915 0.99680
1.03306 1.00017 0.93102
0.00000 0.95632 1.02969 0.00000
0.96054 1.00945 1.01071 0.94114 0.98078
1.04740 1.02210 1.01577 0.93988 0.93903 0.00000
0.00000 0.96939 1.04740 0.00000 0.95421 1.03306 0.93861
0.96433 1.01957 1.02716 0.96517 1.01451 1.02252 1.00861 1.00776
1.03011 1.03644 1.03728 1.03053 1.03433 1.03559 1.02547 1.00270 0.90403

2L Pin Uncertainties
----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%

2M Pin Powers
----------------------------------
0.00000
0.98361 1.03948
0.98407 1.03902 1.03856
0.00000 0.98361 0.98315 0.00000
0.98361 1.03719 1.03581 0.97674 1.02025
0.98178 1.03581 1.03444 0.97125 0.96987 0.00000
0.00000 0.97812 0.97812 0.00000 0.96987 0.96621 1.00376
0.97308 1.01841 1.02986 0.97949 1.01750 1.01567 0.94377 1.01475
1.00742 0.94240 1.03307 1.02940 0.94698 1.03215 1.03627 1.02986 0.94148

2M Pin Uncertainties
----------------------------------
0.000%
0.032%  0.030%
0.032%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%

2N Pin Powers
----------------------------------
0.00000
0.97558 1.02708
0.89949 0.99641 1.02214
0.00000 0.89241 0.96653 0.00000
0.86901 0.97261 1.00630 0.94743 0.95535
0.86694 0.96405 0.96940 0.86416 0.84601 0.00000
0.00000 0.88099 0.88227 0.00000 0.86951 0.91018 1.05380
0.92477 1.01570 1.01818 0.93150 1.03549 1.08249 1.12801 1.15374
1.08150 1.09338 1.09684 1.09239 1.11911 1.14681 1.16660 1.16066 1.05974

2N Pin Uncertainties
----------------------------------
0.000%
0.035%  0.030%
0.035%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.035%  0.021%  0.021%  0.021%  0.030%
0.035%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.035%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
```

```
2O Pin Powers
----------------------------------
0.00000
1.10585 1.07145
1.08988 1.05097 1.01738
0.00000 1.04155 0.98052 0.00000
1.04810 0.96537 0.22011 0.98790 1.03704
1.07309 1.02230 0.97643 1.05548 1.08210 0.00000
0.00000 1.09316 1.08292 0.00000 1.08005 0.99281 0.21986
1.10585 1.07718 1.07227 1.09275 1.04769 0.99199 0.92400 0.96250
1.07677 1.07063 1.06735 1.06408 1.04196 1.01575 0.99199 0.99854 1.01657


2O Pin Uncertainties
----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.035%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.050%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%


2P Pin Powers
----------------------------------
0.00000
1.16949 1.11072
1.14265 1.05287 0.24639
0.00000 1.11812 1.06351 0.00000
1.06536 1.08249 1.08804 1.06351 0.24658
0.24815 1.03945 1.09591 1.10887 1.06074 0.00000
0.00000 1.11488 1.10702 0.00000 1.08110 1.03806 0.24528
1.14913 1.10887 1.03204 0.24644 1.00613 1.03991 1.00335 1.05981
1.13340 1.11442 1.06305 0.99409 1.04269 1.07462 1.08156 1.10470 1.13016


2P Pin Uncertainties
----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.050%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.050%
0.057%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.050%
0.028%  0.021%  0.021%  0.035%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%


2A @ 600K Pin Powers – not an official problem
----------------------------------
0.00000
1.03611 1.00885
1.03647 1.01031 1.01031
0.00000 1.03684 1.03865 0.00000
1.03538 1.00885 1.01176 1.04520 1.03211
1.03248 1.00631 1.00922 1.04447 1.05065 0.00000
0.00000 1.02593 1.02739 0.00000 1.03575 1.01685 0.97397
1.01140 0.98814 0.98814 1.01140 0.98305 0.96561 0.94853 0.93908
0.97687 0.97251 0.97179 0.97397 0.96488 0.95507 0.94635 0.94198 0.94780


2A @ 600K Pin Uncertainties – not an official problem
----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.028%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
```

```
2G @ 300K Pin Powers – not an official problem
----------------------------------
0.00000
1.10010 1.04976
0.94420 0.97230 0.94508
0.00000 0.88721 0.87773 0.00000
0.87519 0.92450 0.91825 0.85339 0.87255
0.87886 0.92993 0.92450 0.85457 0.84714 0.00000
0.00000 0.90657 0.90559 0.00000 0.89958 0.95588 1.06344
0.96160 1.00675 1.01017 0.97313 1.03510 1.08984 1.14506 1.19149
1.07664 1.08544 1.09032 1.09277 1.12160 1.15679 1.19589 1.22961 1.26186

2G @ 300K Pin Uncertainties – not an official problem
----------------------------------
0.000%
0.028%  0.030%
0.035%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.035%  0.021%  0.021%  0.021%  0.030%
0.035%  0.021%  0.021%  0.021%  0.021%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.032%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.028%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%

2H @ 300K Pin Powers – not an official problem
----------------------------------
0.00000
1.08705 1.03508
0.92553 0.95352 0.92479
0.00000 0.86452 0.85422 0.00000
0.85142 0.90234 0.89505 0.82939 0.84925
0.85818 0.91153 0.90471 0.83304 0.82844 0.00000
0.00000 0.89336 0.89272 0.00000 0.89463 0.96266 1.08494
0.95912 1.00513 1.00983 0.97618 1.04638 1.11135 1.17896 1.23495
1.08230 1.09233 1.09920 1.10554 1.14251 1.18741 1.23812 1.28090 1.31946

2H @ 300K Pin Uncertainties – not an official problem
----------------------------------
0.000%
0.035%  0.030%
0.035%  0.021%  0.030%
0.000%  0.025%  0.021%  0.000%
0.035%  0.021%  0.021%  0.028%  0.030%
0.035%  0.021%  0.021%  0.028%  0.028%  0.000%
0.000%  0.021%  0.021%  0.000%  0.021%  0.021%  0.030%
0.035%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%
0.032%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.021%  0.030%

No ENDF/B-VI Results for Problem 2Q
```

APPENDIX D – PROBLEM 3 RESULTS

This appendix contains power distriution results of Problem 3 CE KENO-VI calculations using <u>ENDF/B-VII.0</u> cross sections in ASCII form.

```
Case  k-eff     Sigma
3A  1.175722  0.000005
3B  1.000154  0.000006

3A Radial Pin Powers
-----------------------------------
0.00000
1.03563  1.00956
1.03626  1.00997  1.01066
0.00000  1.03651  1.03819  0.00000
1.03491  1.00906  1.01168  1.04425  1.03171
1.03178  1.00607  1.00914  1.04433  1.04999  0.00000
0.00000  1.02556  1.02706  0.00000  1.03498  1.01662  0.97390
1.01117  0.98830  0.98842  1.01087  0.98351  0.96561  0.94907  0.93975
0.97713  0.97289  0.97247  0.97459  0.96550  0.95585  0.94678  0.94256  0.94786

3A Radial Pin Uncertainties
-----------------------------------
0.000%
0.006%  0.006%
0.006%  0.004%  0.006%
0.000%  0.004%  0.004%  0.000%
0.006%  0.004%  0.004%  0.004%  0.006%
0.006%  0.004%  0.004%  0.004%  0.004%  0.000%
0.000%  0.004%  0.004%  0.000%  0.004%  0.004%  0.006%
0.006%  0.004%  0.004%  0.004%  0.004%  0.004%  0.004%  0.006%
0.006%  0.004%  0.004%  0.004%  0.004%  0.004%  0.004%  0.004%  0.006%

3B Radial Pin Powers
-----------------------------------
0.00000
1.05307  1.02762
0.95863  0.99449  1.02469
0.00000  0.95682  1.04619  0.00000
0.95901  0.99337  1.01736  1.02469  0.96480
1.05725  1.02852  0.98505  0.92289  0.88842  0.00000
0.00000  1.06281  0.95604  0.00000  0.88942  0.90774  0.96658
1.09325  1.05375  0.99867  0.93944  0.96403  0.98531  1.01111  1.03475
1.07184  1.05802  1.03306  1.01049  1.01253  1.02309  1.03907  1.05543  1.07291

3B Radial Pin Uncertainties
-----------------------------------
0.000%
0.006%  0.006%
0.006%  0.004%  0.006%
0.000%  0.005%  0.004%  0.000%
0.006%  0.004%  0.004%  0.004%  0.006%
0.006%  0.004%  0.004%  0.005%  0.005%  0.000%
0.000%  0.004%  0.005%  0.000%  0.005%  0.005%  0.006%
0.006%  0.004%  0.004%  0.005%  0.005%  0.004%  0.004%  0.006%
0.006%  0.004%  0.004%  0.004%  0.004%  0.004%  0.004%  0.004%  0.006%
```

Problem 3 Axial Power Results

Level	Elevation*	Thickness*	3A POWER	3B POWER
49	377.711	7.9212	0.17166 +/- 0.009%	0.18312 +/- 0.009%
48	369.7898	7.9212	0.24941 +/- 0.007%	0.25469 +/- 0.008%
47	361.8686	7.9212	0.34668 +/- 0.006%	0.35096 +/- 0.007%
46	353.9474	7.9212	0.44235 +/- 0.005%	0.44547 +/- 0.006%
45	346.0262	7.9212	0.53052 +/- 0.005%	0.53161 +/- 0.005%
44	338.105	3.81	0.56887 +/- 0.007%	0.56589 +/- 0.007%
43	334.295	8.065	0.66502 +/- 0.004%	0.66528 +/- 0.005%
42	326.23	8.065	0.75936 +/- 0.004%	0.76009 +/- 0.004%
41	318.165	8.065	0.84438 +/- 0.004%	0.84472 +/- 0.004%
40	310.1	8.065	0.92588 +/- 0.004%	0.92521 +/- 0.004%
39	302.035	8.065	1.00378 +/- 0.004%	1.00166 +/- 0.004%
38	293.97	8.065	1.06708 +/- 0.003%	1.06193 +/- 0.004%
37	285.905	3.81	1.06292 +/- 0.005%	1.05119 +/- 0.005%
36	282.095	8.065	1.16570 +/- 0.003%	1.16009 +/- 0.004%
35	274.03	8.065	1.23691 +/- 0.003%	1.23312 +/- 0.003%
34	265.965	8.065	1.29183 +/- 0.003%	1.28808 +/- 0.003%
33	257.9	8.065	1.34148 +/- 0.003%	1.33725 +/- 0.003%
32	249.835	8.065	1.38579 +/- 0.003%	1.38059 +/- 0.003%
31	241.77	8.065	1.41065 +/- 0.003%	1.40262 +/- 0.003%
30	233.705	3.81	1.36407 +/- 0.004%	1.34781 +/- 0.005%
29	229.895	8.065	1.45468 +/- 0.003%	1.44648 +/- 0.003%
28	221.83	8.065	1.48986 +/- 0.003%	1.48459 +/- 0.003%
27	213.765	8.065	1.50467 +/- 0.003%	1.50024 +/- 0.003%
26	205.7	8.065	1.51357 +/- 0.003%	1.50921 +/- 0.003%
25	197.635	8.065	1.51653 +/- 0.003%	1.51133 +/- 0.003%
24	189.57	8.065	1.49862 +/- 0.003%	1.49098 +/- 0.003%
23	181.505	3.81	1.41795 +/- 0.004%	1.40185 +/- 0.005%
22	177.695	8.065	1.47993 +/- 0.003%	1.47282 +/- 0.003%
21	169.63	8.065	1.47284 +/- 0.003%	1.46893 +/- 0.003%
20	161.565	8.065	1.44481 +/- 0.003%	1.44265 +/- 0.003%
19	153.5	8.065	1.41136 +/- 0.003%	1.40950 +/- 0.003%
18	145.435	8.065	1.37204 +/- 0.003%	1.37027 +/- 0.003%
17	137.37	8.065	1.31438 +/- 0.003%	1.31074 +/- 0.003%
16	129.305	3.81	1.21448 +/- 0.005%	1.20371 +/- 0.005%
15	125.495	8.065	1.23644 +/- 0.003%	1.23397 +/- 0.003%
14	117.43	8.065	1.18801 +/- 0.003%	1.18879 +/- 0.004%
13	109.365	8.065	1.12254 +/- 0.003%	1.12492 +/- 0.004%
12	101.3	8.065	1.05270 +/- 0.003%	1.05613 +/- 0.004%
11	93.235	8.065	0.97853 +/- 0.004%	0.98264 +/- 0.004%
10	85.17	8.065	0.89182 +/- 0.004%	0.89532 +/- 0.004%
9	77.105	3.81	0.79068 +/- 0.006%	0.78969 +/- 0.006%
8	73.295	8.2111	0.76820 +/- 0.004%	0.77329 +/- 0.004%
7	65.0839	8.2112	0.68569 +/- 0.004%	0.69336 +/- 0.005%
6	56.8727	8.2111	0.59265 +/- 0.005%	0.60190 +/- 0.005%
5	48.6616	8.2112	0.49716 +/- 0.005%	0.50769 +/- 0.005%
4	40.4504	8.2111	0.39929 +/- 0.006%	0.41069 +/- 0.006%
3	32.2393	8.2112	0.29915 +/- 0.006%	0.31134 +/- 0.007%
2	24.0281	8.2111	0.19703 +/- 0.008%	0.21087 +/- 0.008%
1	15.817	3.866	0.13945 +/- 0.014%	0.16628 +/- 0.013%
0	11.951			

*dimensions in cm

APPENDIX E – PROBLEM 4 RESULTS

This appendix contains axial and assembly radial power distributions of Problem 4 CE KENO-VI calculations using <u>ENDF/B-VII.0</u>

Level	Elev*	Thick*	Average Power	Assy 1 (H-8)	Assy 1 (H-9)	Assy 1 (G-9)
49	377.711	7.9212	0.03762 +/- 0.013%	0.01986 +/- 0.056%	0.03593 +/- 0.029%	0.04375 +/- 0.019%
48	369.7898	7.9212	0.05630 +/- 0.011%	0.03064 +/- 0.045%	0.05242 +/- 0.024%	0.06659 +/- 0.015%
47	361.8686	7.9212	0.08093 +/- 0.009%	0.04570 +/- 0.037%	0.07519 +/- 0.020%	0.09547 +/- 0.013%
46	353.9474	7.9212	0.10750 +/- 0.008%	0.06188 +/- 0.031%	0.09987 +/- 0.017%	0.12654 +/- 0.011%
45	346.0262	7.9212	0.13493 +/- 0.007%	0.07789 +/- 0.028%	0.12530 +/- 0.015%	0.15883 +/- 0.010%
44	338.105	3.81	0.15028 +/- 0.009%	0.08621 +/- 0.038%	0.13900 +/- 0.021%	0.17759 +/- 0.013%
43	334.295	8.065	0.18360 +/- 0.006%	0.10606 +/- 0.024%	0.17052 +/- 0.013%	0.21607 +/- 0.008%
42	326.23	8.065	0.22366 +/- 0.005%	0.12916 +/- 0.022%	0.20775 +/- 0.012%	0.26319 +/- 0.008%
41	318.165	8.065	0.26726 +/- 0.005%	0.15437 +/- 0.020%	0.24828 +/- 0.011%	0.31447 +/- 0.007%
40	310.1	8.065	0.31729 +/- 0.005%	0.18342 +/- 0.018%	0.29485 +/- 0.010%	0.37320 +/- 0.006%
39	302.035	8.065	0.37496 +/- 0.004%	0.21716 +/- 0.017%	0.34858 +/- 0.009%	0.44080 +/- 0.006%
38	293.97	8.065	0.43695 +/- 0.004%	0.25402 +/- 0.015%	0.40650 +/- 0.008%	0.51314 +/- 0.005%
37	285.905	3.81	0.46760 +/- 0.005%	0.27137 +/- 0.022%	0.43371 +/- 0.012%	0.55053 +/- 0.007%
36	282.095	8.065	0.55350 +/- 0.003%	0.32649 +/- 0.014%	0.51638 +/- 0.007%	0.64736 +/- 0.005%
35	274.03	8.065	0.65361 +/- 0.003%	0.39567 +/- 0.012%	0.61175 +/- 0.007%	0.75995 +/- 0.004%
34	265.965	8.065	0.76657 +/- 0.003%	0.50692 +/- 0.011%	0.71897 +/- 0.006%	0.87908 +/- 0.004%
33	257.9	8.065	0.91291 +/- 0.003%	0.81428 +/- 0.009%	0.84297 +/- 0.006%	1.00752 +/- 0.004%
32	249.835	8.065	1.04940 +/- 0.002%	1.01931 +/- 0.008%	0.96694 +/- 0.005%	1.13937 +/- 0.004%
31	241.77	8.065	1.16275 +/- 0.002%	1.14877 +/- 0.007%	1.07288 +/- 0.005%	1.25611 +/- 0.003%
30	233.705	3.81	1.18887 +/- 0.003%	1.18313 +/- 0.010%	1.09309 +/- 0.007%	1.28609 +/- 0.005%
29	229.895	8.065	1.32973 +/- 0.002%	1.32365 +/- 0.007%	1.22826 +/- 0.005%	1.43271 +/- 0.003%
28	221.83	8.065	1.44367 +/- 0.002%	1.43981 +/- 0.007%	1.33405 +/- 0.005%	1.55425 +/- 0.003%
27	213.765	8.065	1.53483 +/- 0.002%	1.53212 +/- 0.006%	1.41841 +/- 0.004%	1.65194 +/- 0.003%
26	205.7	8.065	1.61556 +/- 0.002%	1.61280 +/- 0.006%	1.49310 +/- 0.004%	1.73870 +/- 0.003%
25	197.635	8.065	1.68561 +/- 0.002%	1.68326 +/- 0.006%	1.55790 +/- 0.004%	1.81391 +/- 0.003%
24	189.57	8.065	1.72692 +/- 0.002%	1.72450 +/- 0.006%	1.59596 +/- 0.004%	1.85848 +/- 0.003%
23	181.505	3.81	1.67670 +/- 0.003%	1.67750 +/- 0.009%	1.54302 +/- 0.006%	1.81017 +/- 0.004%
22	177.695	8.065	1.78849 +/- 0.002%	1.78594 +/- 0.006%	1.65290 +/- 0.004%	1.92472 +/- 0.003%
21	169.63	8.065	1.83085 +/- 0.002%	1.82840 +/- 0.006%	1.69222 +/- 0.004%	1.97008 +/- 0.003%
20	161.565	8.065	1.84279 +/- 0.002%	1.84030 +/- 0.006%	1.70313 +/- 0.004%	1.98308 +/- 0.003%
19	153.5	8.065	1.84254 +/- 0.002%	1.83979 +/- 0.006%	1.70298 +/- 0.004%	1.98278 +/- 0.003%
18	145.435	8.065	1.83017 +/- 0.002%	1.82761 +/- 0.006%	1.69151 +/- 0.004%	1.96948 +/- 0.003%
17	137.37	8.065	1.78756 +/- 0.002%	1.78524 +/- 0.006%	1.65192 +/- 0.004%	1.92378 +/- 0.003%
16	129.305	3.81	1.67553 +/- 0.003%	1.67666 +/- 0.009%	1.54180 +/- 0.006%	1.80899 +/- 0.004%
15	125.495	8.065	1.72564 +/- 0.002%	1.72313 +/- 0.006%	1.59481 +/- 0.004%	1.85711 +/- 0.003%
14	117.43	8.065	1.68375 +/- 0.002%	1.68174 +/- 0.006%	1.55621 +/- 0.004%	1.81180 +/- 0.003%
13	109.365	8.065	1.61318 +/- 0.002%	1.61115 +/- 0.006%	1.49089 +/- 0.004%	1.73597 +/- 0.003%
12	101.3	8.065	1.53192 +/- 0.002%	1.52995 +/- 0.006%	1.41580 +/- 0.004%	1.64852 +/- 0.003%
11	93.235	8.065	1.44044 +/- 0.002%	1.43874 +/- 0.007%	1.33130 +/- 0.005%	1.55000 +/- 0.003%
10	85.17	8.065	1.32621 +/- 0.002%	1.32406 +/- 0.007%	1.22568 +/- 0.005%	1.42729 +/- 0.003%
9	77.105	3.81	1.18506 +/- 0.003%	1.18562 +/- 0.010%	1.09056 +/- 0.007%	1.27941 +/- 0.005%
8	73.295	8.2111	1.15756 +/- 0.002%	1.15580 +/- 0.007%	1.06978 +/- 0.005%	1.24578 +/- 0.003%
7	65.0839	8.2112	1.04136 +/- 0.002%	1.03989 +/- 0.008%	0.96251 +/- 0.005%	1.12058 +/- 0.004%
6	56.8727	8.2111	0.90599 +/- 0.003%	0.90489 +/- 0.008%	0.83739 +/- 0.006%	0.97487 +/- 0.004%
5	48.6616	8.2112	0.76454 +/- 0.003%	0.76379 +/- 0.009%	0.70663 +/- 0.006%	0.82264 +/- 0.004%
4	40.4504	8.2111	0.61721 +/- 0.003%	0.61660 +/- 0.010%	0.57071 +/- 0.007%	0.66386 +/- 0.005%
3	32.2393	8.2112	0.46490 +/- 0.004%	0.46488 +/- 0.011%	0.43040 +/- 0.008%	0.49940 +/- 0.005%
2	24.0281	8.2111	0.30876 +/- 0.005%	0.30796 +/- 0.014%	0.28842 +/- 0.010%	0.32930 +/- 0.007%
1	15.817	3.866	0.22264 +/- 0.008%	0.21227 +/- 0.024%	0.22328 +/- 0.016%	0.22459 +/- 0.012%
0	11.951					

*dimensions in cm

```
Assembly Radial Powers
-----------------------
  0.95571
  0.92490  1.08617

 Assembly Radial Power Uncertainties
-------------------------------------
  0.001%
  0.001%  0.001%
```

APPENDIX F – PROBLEM 5 RESULTS

This appendix contains and axial and assembly radial power distribution results of Problem 5 CE KENO-VI calculations using ENDF/B-VII.0

Problem 5 Average Axial Power Results

```
Level    Elevation*   Thickness*      Axial Power
----------------------------------------------------
49       377.711      7.9212       0.08863 +/- 0.006%
48       369.7898     7.9212       0.13161 +/- 0.005%
47       361.8686     7.9212       0.18578 +/- 0.004%
46       353.9474     7.9212       0.24150 +/- 0.004%
45       346.0262     7.9212       0.29602 +/- 0.003%
44       338.105      3.81         0.32305 +/- 0.005%
43       334.295      8.065        0.38714 +/- 0.003%
42       326.23       8.065        0.45741 +/- 0.003%
41       318.165      8.065        0.52826 +/- 0.002%
40       310.1        8.065        0.60395 +/- 0.002%
39       302.035      8.065        0.68561 +/- 0.002%
38       293.97       8.065        0.76578 +/- 0.002%
37       285.905      3.81         0.79413 +/- 0.003%
36       282.095      8.065        0.91781 +/- 0.002%
35       274.03       8.065        1.02719 +/- 0.002%
34       265.965      8.065        1.12040 +/- 0.002%
33       257.9        8.065        1.20747 +/- 0.002%
32       249.835      8.065        1.28822 +/- 0.002%
31       241.77       8.065        1.34777 +/- 0.002%
30       233.705      3.81         1.32647 +/- 0.002%
29       229.895      8.065        1.44194 +/- 0.001%
28       221.83       8.065        1.51016 +/- 0.001%
27       213.765      8.065        1.55569 +/- 0.001%
26       205.7        8.065        1.59256 +/- 0.001%
25       197.635      8.065        1.62076 +/- 0.001%
24       189.57       8.065        1.62338 +/- 0.001%
23       181.505      3.81         1.54917 +/- 0.002%
22       177.695      8.065        1.63459 +/- 0.001%
21       169.63       8.065        1.64724 +/- 0.001%
20       161.565      8.065        1.63418 +/- 0.001%
19       153.5        8.065        1.61212 +/- 0.001%
18       145.435      8.065        1.58100 +/- 0.001%
17       137.37       8.065        1.52594 +/- 0.001%
16       129.305      3.81         1.41595 +/- 0.002%
15       125.495      8.065        1.45172 +/- 0.001%
14       117.43       8.065        1.40566 +/- 0.002%
13       109.365      8.065        1.33696 +/- 0.002%
12       101.3        8.065        1.26097 +/- 0.002%
11        93.235      8.065        1.17803 +/- 0.002%
10        85.17       8.065        1.07791 +/- 0.002%
 9        77.105      3.81         0.95729 +/- 0.003%
 8        73.295      8.2111       0.93441 +/- 0.002%
 7        65.0839     8.2112       0.83815 +/- 0.002%
 6        56.8727     8.2111       0.72747 +/- 0.002%
 5        48.6616     8.2112       0.61278 +/- 0.002%
 4        40.4504     8.2111       0.49411 +/- 0.003%
 3        32.2393     8.2112       0.37199 +/- 0.003%
 2        24.0281     8.2111       0.24738 +/- 0.004%
 1        15.817      3.866        0.18084 +/- 0.006%
 0        11.951
```

*dimensions in cm

Problem 5 Assembly Radial Power Results

Assembly Radial Powers

```
  0.94865
  0.91928  0.99730
  1.01805  0.90832  1.06477
  0.98503  1.08193  1.04117  1.16152
  1.06467  1.04706  1.17457  1.08499  1.23684
  1.04796  1.16188  1.15202  1.15082  0.89694  0.91255
  1.08407  1.06524  1.10393  1.04960  0.94517  0.62956
  0.79308  0.90712  0.80461  0.65895
```

 Assembly Radial Power Uncertainties

```
  0.004%
  0.003%  0.002%
  0.003%  0.002%  0.002%
  0.003%  0.002%  0.002%  0.002%
  0.003%  0.002%  0.002%  0.002%  0.002%
  0.003%  0.002%  0.002%  0.002%  0.002%  0.002%
  0.002%  0.002%  0.002%  0.002%  0.002%  0.002%
  0.003%  0.002%  0.002%  0.002%
```

APPENDIX G – PROBLEM 5 KENO-VI ITC CALCULATION

The HZP ARO isothermal temperature coefficient (ITC) has been estimated for WBN1C1 using the detailed CE KENO-VI model described in this document. However, due to the direct approach to using the continuous energy cross section data, KENO cannot easily implement the temperature perturbation approach which is typically employed for these types of calculations. Furthermore, the stochastic nature of the Monte Carlo method can result in substantial errors for calculations based on small reactivity changes, if the estimated uncertainty in reactivity represents a significant fraction of the actual reactivity change.

Two main limitations in the current KENO version complicate its use for this type of calculation. First, no temperature interpolation for Doppler broadening is performed. The AMPX data is provided and used directly in the transport calculation. Libraries exist at 565K (the HZP temperature) and 600K, but intermediate temperatures needed for the temperature perturbations (4F to 5K) are not available; in addition, the reactivity trends between 565K and 600K are not necessarily indicative of the trend from small temperature changes.

The second current limitation regards the availability and current use of $S(\alpha,\beta)$ continuous energy neutron scattering data for the H-1 isotope. The current ENDF/B-VII.0 data includes this data only at 550K and 600K (and other 50K increments), and KENO performs no interpolation, but rather applies the value available in the library at the nearest temperature input in the model. In addition, KENO does not permit different temperatures in isotopes belonging to the same composition (e.g. H-1 and O-16). For these reasons, it is not possible to perform a small moderator temperature perturbation at 565K and, as will be shown, this effect can be significant.

In order to overcome these limitations, the following methodology was utilized for this analysis:

- A development version of KENO was provided by the ORNL SCALE team which permitted setting the temperature of individual isotopes (mainly H-1) uniquely from other isotopes and compositions. This has been accomplished by manipulation of the cross section data files.

- New Doppler-broadened CE libraries have been created and provided by the ORNL SCALE team at temperatures between 550K and 580K, at 5K increments (six additional libraries). These libraries were generated with AMPX consistent with the methods employed to generate the 565K and 600K library. Note that the $S(\alpha,\beta)$ data for these libraries remained at either 550K or 600K, depending on which was closest to the library temperature.

- The ITC calculation has been split in three individual simulations, and the results later combined. These three simulations are described further down: a Moderator Temperature-Only Coefficient, a Moderator Density Coefficient (MDC) and a Doppler Temperature Coefficient (DTC).

- Rather than directly using the reactivity delta from single state-point calculations at a few perturbed temperatures, which can be sensitive to non-physical variation from the Monte Carlo stochastic process, results have been generated for all temperatures between 550K and 580K. These reactivity points have then been fit with a polynomial, and the slope of the curve at the 565K ITC temperature has been used as representative of the relevant reactivity coefficient (e.g. MTC, MDC, and DTC). This method ensures that the reactivity coefficient calculation relies on a smoothly varying reactivity trend vs. temperature.

- The uncertainty in the above procedure is estimated using a separate Monte Carlo sampling procedure. The uncertainties of each of the input KENO eigenvalues were propagated to the final coefficients by sampling each datapoint from a normal distribution based on the calculated KENO mean and sigma, and fitting the calculated data as described in the previous item. 100,000 ITC's were calculated in this manner, each one based on sixteen independently sampled eigenvalues. The final uncertainty in the calculated ITC was estimated as the standard deviation of this very large population of ITC's.

The KENO cases used for these calculations relied on 7.5e9 particles (1500 generations with 5e6 particles per generation, skipping the first 500 generations). Each calculation took approximately 37 hours on 200 cores on the Fission supercomputer at Idaho National Laboratory.

1. Moderator Temperature-Only Coefficient

The worth of the WBN1C1 moderator temperature was calculated by perturbing the H-1 temperature from 550K to 600K. As mentioned, due to the lack of temperature interpolation on the scattering data, these are the only temperatures for which KENO calculations are possible. Thus, these simulations capture essentially the reactivity worth of the change in $S(\alpha,\beta)$ data over a 50K temperature interval from 550K to 600K. The trend is assumed to be linear, and calculations performed at 500K have confirmed this. The results are shown in Table G-1. It should be noted that this not a typical MTC calculation, where both density and temperature are perturbed simultaneously. The impact of the density variation is assessed separately.

Note also that the KENO result implies that all KENO core eigenvalues calculated at 565K should be adjusted by approximately -42 pcm for the lack of temperature dependence in the $S(\alpha,\beta)$ scattering data treatment. The KENO reference results reported in the main section of this document incorporate this adjustment.

Table G-1: Moderator Temperature-Only Reactivity Coefficient

Temperature (K)	Eigenvalue
550	0.999876 ± 0.000011
600	0.998485 ± 0.000010
Coefficient	**-1.55 ± 0.03 pcm/F**

2. Moderator Density Coefficient (MDC)

The KENO moderator density calculations were performed at 565K for all materials except for H-1, which used the nearest temperature of 550K, and the corresponding water density at each temperature between 550K and 580K, in 5K increments. The results are provided in Table G-2 and Figure G-1. The MDC was calculated by evaluating the derivative of the parabolic fit at 565K.

Table G-2: Moderator Density Reactivity Coefficient

Temperature (K)	Density (g/cc)	Eigenvalue
550	0.76972	0.999719 ± 0.000011
555	0.76106	0.999792 ± 0.000010
560	0.75207	0.999855 ± 0.000011
565	0.74271	0.999869 ± 0.000011
570	0.73294	0.999837 ± 0.000010
575	0.72269	0.999777 ± 0.000010
580	0.71190	0.999664 ± 0.000010
Coefficient	**-0.08 ± 0.02 pcm/F**	

Figure G-1: KENO Reactivity vs. Moderator Density

Trendline:
$y = -7.795E\text{-}07x^2 + 8.793E\text{-}04x + 7.519E\text{-}01$
$R^2 = 9.940E\text{-}01$
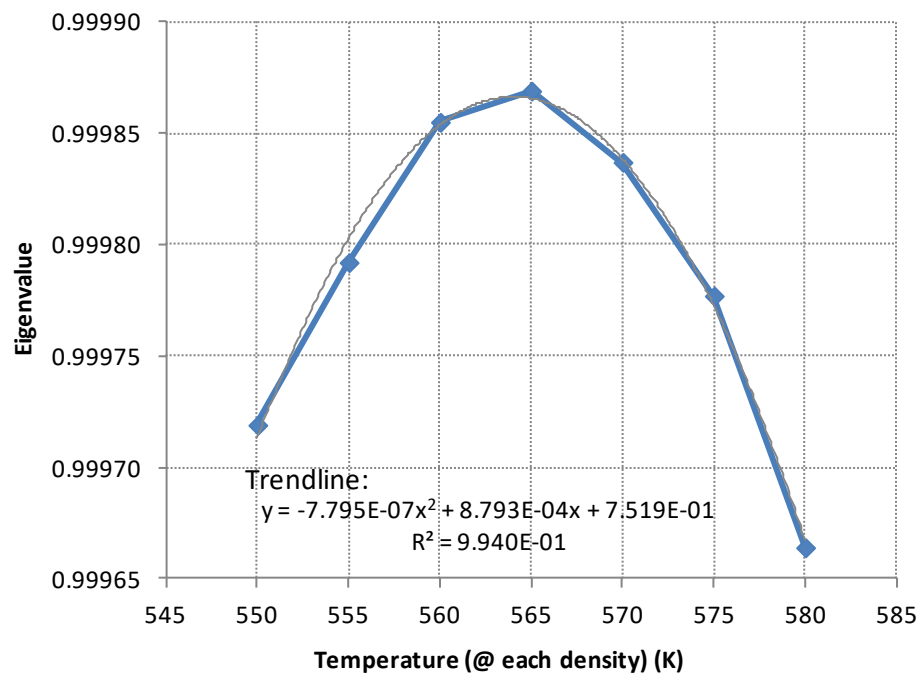
Combining the moderator density and temperature components, the effective Moderator Temperature Coefficient (MTC) for WBN1C1 is calculated to be **-1.63 ± 0.03 pcm/F**.

3. Doppler Temperature Coefficient (DTC)

The KENO DTC is estimated using the Doppler-broadened libraries provided by the SCALE development team at 5K temperature increments. The temperature of all materials and isotopes other than H-1 is perturbed along with the fuel temperature. Calculations have been performed showing very small reactivity impact from the varying temperature for these other materials. For these KENO simulations, the H-1 temperature is fixed at 550K and the moderator density is held at the 565K value. The results are provided in Table G-3 and Figure G-2. The DTC was calculated by evaluating the derivative of the linear fit at 565K.

Table G-3: Doppler Temperature Reactivity Coefficient

Temperature (K)	Eigenvalue
550	1.000383 ± 0.000011
555	1.000232 ± 0.000010
560	1.000104 ± 0.000011
565	0.999965 ± 0.000011
570	0.999814 ± 0.000010
575	0.999674 ± 0.000011
580	0.999548 ± 0.000011
Coefficient	-1.55 ± 0.02 pcm/F

Figure G-2: KENO Reactivity vs. Fuel Temperature

Trendline:
$y = -2.794E\text{-}05x + 1.016E+00$
$R^2 = 9.995E\text{-}01$
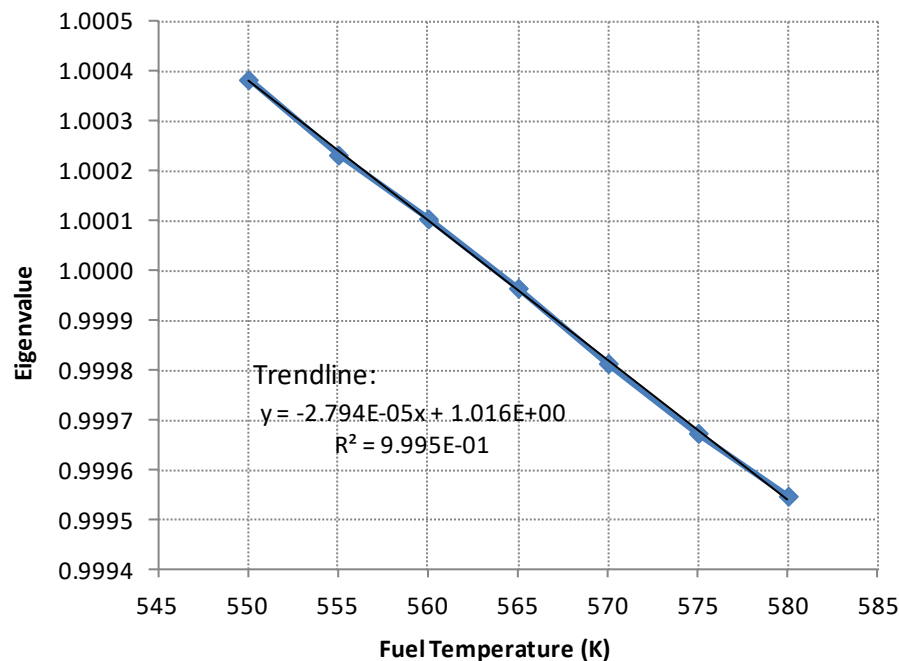
Combining the moderator temperature and fuel temperature components, the Isothermal Temperature Coefficient (ITC) for WBN1C1 is calculated to be **-3.18 ± 0.04 pcm/F**.

APPENDIX H – PROBLEM 4-2D DATA AND RESULTS

The following are the isotopics and results for Problem 4-2D, in ASCII form.

ENDF/B-VII.0

```
mixture = fuel (2.11%)                      Mixture = pyrex
  8016   4.57591E-02                         5010   9.63266E-04
 92234   4.04814E-06                         5011   3.90172E-03
 92235   4.88801E-04                         8016   4.67761E-02
 92236   2.23756E-06                        14028   1.81980E-02
 92238   2.23844E-02                        14029   9.24474E-04
                                            14030   6.10133E-04
mixture = fuel (2.619%)
  8016   4.57617E-02                        mixture = stainless steel
 92234   5.09503E-06                         6000   3.20895E-04
 92235   6.06709E-04                        14028   1.58197E-03
 92236   2.76809E-06                        14029   8.03653E-05
 92238   2.22663E-02                        14030   5.30394E-05
                                            15031   6.99938E-05
mixture = gap                               24050   7.64915E-04
  2004   2.68714E-05                         24052   1.47506E-02
                                            24053   1.67260E-03
mixture =  cladding (zircaloy-4)            24054   4.16346E-04
 24050   3.30121E-06                         25055   1.75387E-03
 24052   6.36606E-05                         26054   3.44776E-03
 24053   7.21860E-06                         26056   5.41225E-02
 24054   1.79686E-06                         26057   1.24992E-03
 26054   8.68307E-06                         26058   1.66342E-04
 26056   1.36306E-04                         28058   5.30854E-03
 26057   3.14789E-06                         28060   2.04484E-03
 26058   4.18926E-07                         28061   8.88879E-05
 40090   2.18865E-02                         28062   2.83413E-04
 40091   4.77292E-03                         28064   7.21770E-05
 40092   7.29551E-03
 40094   7.39335E-03                        mixture = AIC
 40096   1.19110E-03                         47107   2.36159E-02
 50112   4.68066E-06                         47109   2.19403E-02
 50114   3.18478E-06                         48106   3.41523E-05
 50115   1.64064E-06                         48108   2.43165E-05
 50116   7.01616E-05                         48110   3.41250E-04
 50117   3.70592E-05                         48111   3.49720E-04
 50118   1.16872E-04                         48112   6.59276E-04
 50119   4.14504E-05                         48113   3.33873E-04
 50120   1.57212E-04                         48114   7.84957E-04
 50122   2.23417E-05                         48116   2.04641E-04
 50124   2.79392E-05                         49113   3.44262E-04
 72174   3.54138E-09                         49115   7.68050E-03
 72176   1.16423E-07
 72177   4.11686E-07                        mixture = B4C
 72178   6.03806E-07                         5010   1.52689E-02
 72179   3.01460E-07                         5011   6.14591E-02
 72180   7.76449E-07                         6000   1.91820E-02

mixture = moderator
  1001   4.96224E-02
  5010   1.07070E-05
  5011   4.30971E-05
  8016   2.48112E-02
```

ENDF/B-VI.8

mixture = fuel (2.11%)
  8016   4.57591E-02
 92234   4.04814E-06
 92235   4.88801E-04
 92236   2.23756E-06
 92238   2.23844E-02

mixture = fuel (2.619%)
  8016   4.57617E-02
 92234   5.09503E-06
 92235   6.06709E-04
 92236   2.76809E-06
 92238   2.22663E-02

mixture = gap
  2004   2.68714E-05

mixture = moderator
  1001   4.96224E-02
  5010   1.07070E-05
  5011   4.30971E-05
  8016   2.48112E-02

Mixture = pyrex
  5010   9.63266E-04
  5011   3.90172E-03
  8016   4.67761E-02
 14000   1.97326E-02

mixture = AIC
 47107   2.36159E-02
 47109   2.19403E-02
 48000   2.73220E-03
 49000   8.02477E-03

mixture = cladding (zircaloy-4)
 24050   3.30121E-06
 24052   6.36606E-05
 24053   7.21860E-06
 24054   1.79686E-06
 26054   8.68307E-06
 26056   1.36306E-04
 26057   3.14789E-06
 26058   4.18926E-07
 40000   4.25393E-02
 50112   4.68066E-06
 50114   3.18478E-06
 50115   1.64064E-06
 50116   7.01616E-05
 50117   3.70592E-05
 50118   1.16872E-04
 50119   4.14504E-05
 50120   1.57212E-04
 50122   2.23417E-05
 50124   2.79392E-05
 72000   2.21330E-06

mixture = stainless steel
  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

Problem 4-2D ENDF/B-VII.0 Eigenvalue Results

Case	k-eff	Sigma
4A-2D	1.010238	0.000013
4B-2D	0.983446	0.000012
4C-2D	0.980291	0.000013

Problem 4-2D ENDF/B-VI.8 Eigenvalue Results

Case	k-eff	Sigma
4A-2D	1.007160	0.000024
4B-2D	0.980355	0.000026
4C-2D	n/a	

Problem 4-2D ENDF/B-VII.0 Eigenvalue Results @ 565K

Case	k-eff	Sigma
4A-2D	1.012241	0.000009
4B-2D	0.985584	0.000010
4C-2D	0.982344	0.000009

Problem 4-2D ENDF/B-VII.0 Power Results

4A-2D Assembly Powers

  0.99772
  0.92262 1.07795

4A-2D Assembly Power Uncertainties

  0.004%
  0.003% 0.002%

4B-2D Assembly Powers

  0.57019
  0.92597 1.18148

4B-2D Assembly Power Uncertainties

  0.006%
  0.003% 0.002%

4C-2D Assembly Powers

  0.52505
  0.92446 1.19428

4C-2D Assembly Power Uncertainties

  0.006%
  0.003% 0.002%

Problem 4-2D ENDF/B-VII.0 Power Results @ 565K

4A-2D Assembly Powers

  0.99895
  0.92271 1.07755

4A-2D Assembly Uncertainties

  0.004%
  0.003% 0.002%

4B-2D Assembly Powers

  0.57359
  0.92638 1.18022

4B-2D Assembly Uncertainties

  0.006%
  0.003% 0.002%

4C-2D Assembly Powers

  0.52781
  0.92487 1.19317

4C-2D Assembly Uncertainties

  0.006%
  0.003% 0.002%

```
4A-2D Pin Powers
----------------
 Assembly:[1] H-8
  0.00000
  1.07301  1.05093
  1.07187  1.04978  1.04864
  0.00000  1.06768  1.06844  0.00000
  1.06121  1.03988  1.04141  1.06616  1.05169
  1.04940  1.02884  1.02998  1.05854  1.05892  0.00000
  0.00000  1.02846  1.02922  0.00000  1.03455  1.01666  0.97553
  0.99000  0.97249  0.97325  0.99038  0.97172  0.95802  0.94241  0.92908
  0.92032  0.91766  0.91918  0.92184  0.91994  0.91842  0.91651  0.91537  0.91613


 Assembly:[3] H-9
  1.00904  1.01285  1.01437  1.01247  1.02123  1.03265  1.04559  1.06121  1.08519
  0.89405  0.92299  0.92451  0.89786  0.93441  0.96030  0.99152  1.02389  1.06463
  0.00000  0.84493  0.84797  0.00000  0.84188  0.86892  0.93517  0.99419  1.05207
  0.82665  0.86435  0.87387  0.84302  0.82627  0.00000  0.87120  0.96677  1.04179
  0.82932  0.87349  0.91232  0.93060  0.88757  0.82856  0.84645  0.94202  1.03417
  0.00000  0.85978  0.94355  0.00000  0.93251  0.84607  0.00000  0.90776  1.02732
  0.86854  0.89976  0.92717  0.94431  0.91461  0.87958  0.85521  0.93631  1.03151
  0.95231  0.93136  0.90052  0.86092  0.87767  0.87006  0.85331  0.93517  1.03189
  0.00000  0.95192  0.86816  0.00000  0.83274  0.83160  0.00000  0.90737  1.02960
  0.95078  0.92870  0.89824  0.86016  0.87539  0.86930  0.85445  0.93707  1.03531
  0.86435  0.89557  0.92261  0.94050  0.91271  0.87882  0.85635  0.93898  1.03684
  0.00000  0.85216  0.93555  0.00000  0.92794  0.84417  0.00000  0.91156  1.03531
  0.81675  0.86130  0.90014  0.92108  0.87996  0.82513  0.84645  0.94621  1.04407
  0.80723  0.84417  0.85483  0.82779  0.81371  0.00000  0.86854  0.96982  1.05359
  0.00000  0.80990  0.81485  0.00000  0.81751  0.84988  0.92337  0.99343  1.06387
  0.83008  0.85826  0.86244  0.84150  0.88453  0.92070  0.96487  1.01361  1.07415
  0.89062  0.89786  0.90204  0.90623  0.92756  0.95535  0.99000  1.03151  1.08748


 Assembly:[4] G-9
  0.91918
  0.92184  0.93822
  0.92603  0.95497  0.99152
  0.92946  0.97363  1.03646  0.00000
  0.93403  0.98962  1.05740  1.08748  1.08367
  0.93822  1.01361  0.00000  1.09091  1.10233  0.00000
  0.93784  0.99838  1.05930  1.06425  1.08063  1.11337  1.09738
  0.93974  0.99990  1.06121  1.06654  1.08367  1.11794  1.10271  1.10956
  0.94393  1.01932  0.00000  1.09167  1.10994  0.00000  1.13165  1.13812  0.00000
  0.94355  1.00371  1.06692  1.07263  1.09053  1.12670  1.11185  1.11984  1.14878  1.13165
  0.94507  1.00714  1.07149  1.07910  1.09700  1.13127  1.11680  1.12479  1.15373  1.13698  1.14079
  0.95040  1.02770  0.00000  1.11261  1.12784  0.00000  1.14383  1.15069  0.00000  1.16401  1.17049  0.00000
  0.94812  1.00904  1.08405  1.11908  1.11946  1.14345  1.12365  1.12974  1.15944  1.14231  1.14993  1.18343  1.17429
  0.94812  0.99952  1.07111  0.00000  1.13736  1.14459  1.12327  1.12898  1.15830  1.14155  1.14916  1.18648  1.19371  0.00000
  0.94736  0.98886  1.03646  1.09357  1.12403  0.00000  1.14003  1.14650  0.00000  1.16059  1.16706  0.00000  1.18115  1.16630  1.12784
  0.94964  0.98429  1.01666  1.05054  1.08063  1.11528  1.10614  1.11413  1.14117  1.12632  1.13203  1.15640  1.13393  1.11984  1.10614  1.09738
  0.95726  0.98772  1.01589  1.04179  1.06463  1.08405  1.09129  1.10081  1.11071  1.11223  1.11756  1.12365  1.11794  1.11109  1.10309  1.10043  1.10576
```

```
4A-2D Pin Power Uncertainties
-----------------------------
 Assembly:[1] H-8
  0.000%
  0.045%  0.046%
  0.044%  0.032%  0.047%
  0.000%  0.031%  0.032%  0.000%
  0.045%  0.032%  0.033%  0.032%  0.043%
  0.046%  0.032%  0.032%  0.032%  0.032%  0.000%
  0.000%  0.033%  0.032%  0.000%  0.033%  0.033%  0.046%
  0.046%  0.033%  0.034%  0.033%  0.034%  0.033%  0.033%  0.046%
  0.047%  0.034%  0.034%  0.034%  0.034%  0.035%  0.034%  0.034%  0.049%

 Assembly:[3] H-9
  0.046%  0.033%  0.032%  0.033%  0.032%  0.033%  0.032%  0.032%  0.032%
  0.048%  0.035%  0.034%  0.035%  0.034%  0.034%  0.033%  0.032%  0.032%
  0.000%  0.035%  0.035%  0.000%  0.036%  0.035%  0.034%  0.033%  0.032%
  0.052%  0.035%  0.035%  0.035%  0.036%  0.000%  0.036%  0.033%  0.031%
  0.051%  0.035%  0.035%  0.034%  0.035%  0.036%  0.035%  0.034%  0.032%
  0.000%  0.035%  0.034%  0.000%  0.034%  0.036%  0.000%  0.035%  0.032%
  0.050%  0.035%  0.035%  0.034%  0.034%  0.035%  0.036%  0.034%  0.032%
  0.048%  0.034%  0.035%  0.036%  0.036%  0.036%  0.035%  0.033%  0.032%
  0.000%  0.034%  0.035%  0.000%  0.036%  0.036%  0.000%  0.034%  0.032%
  0.047%  0.034%  0.034%  0.036%  0.036%  0.036%  0.035%  0.034%  0.032%
  0.051%  0.035%  0.034%  0.034%  0.035%  0.035%  0.036%  0.034%  0.032%
  0.000%  0.036%  0.034%  0.000%  0.034%  0.035%  0.000%  0.035%  0.032%
  0.051%  0.035%  0.034%  0.035%  0.035%  0.036%  0.035%  0.034%  0.032%
  0.052%  0.036%  0.035%  0.036%  0.036%  0.000%  0.035%  0.034%  0.032%
  0.000%  0.037%  0.036%  0.000%  0.036%  0.036%  0.034%  0.032%  0.031%
  0.051%  0.036%  0.036%  0.036%  0.035%  0.034%  0.033%  0.033%  0.031%
  0.050%  0.035%  0.035%  0.034%  0.034%  0.033%  0.033%  0.032%  0.031%

 Assembly:[4] G-9
  0.049%
  0.034%  0.049%
  0.034%  0.033%  0.047%
  0.033%  0.033%  0.032%  0.000%
  0.035%  0.033%  0.032%  0.031%  0.045%
  0.034%  0.032%  0.000%  0.031%  0.032%  0.000%
  0.034%  0.033%  0.032%  0.031%  0.031%  0.031%  0.046%
  0.034%  0.033%  0.032%  0.031%  0.032%  0.031%  0.032%  0.044%
  0.035%  0.032%  0.000%  0.032%  0.031%  0.000%  0.031%  0.031%  0.000%
  0.033%  0.033%  0.031%  0.031%  0.032%  0.030%  0.030%  0.031%  0.030%  0.043%
  0.034%  0.032%  0.033%  0.032%  0.031%  0.031%  0.032%  0.031%  0.031%  0.031%  0.043%
  0.034%  0.033%  0.000%  0.031%  0.031%  0.000%  0.031%  0.030%  0.000%  0.031%  0.031%  0.000%
  0.034%  0.033%  0.031%  0.031%  0.031%  0.030%  0.031%  0.031%  0.030%  0.030%  0.030%  0.030%  0.042%
  0.034%  0.033%  0.031%  0.000%  0.030%  0.031%  0.031%  0.031%  0.031%  0.031%  0.030%  0.031%  0.030%  0.000%
  0.034%  0.033%  0.032%  0.031%  0.031%  0.000%  0.030%  0.031%  0.000%  0.030%  0.030%  0.000%  0.030%  0.030%  0.044%
  0.033%  0.034%  0.033%  0.031%  0.031%  0.031%  0.031%  0.031%  0.031%  0.031%  0.030%  0.030%  0.031%  0.030%  0.031%  0.044%
  0.034%  0.033%  0.032%  0.032%  0.031%  0.032%  0.031%  0.031%  0.031%  0.031%  0.031%  0.031%  0.031%  0.031%  0.031%  0.032%  0.044%
```

```
4B-2D Pin Powers
-----------------------------------
 Assembly:[1] H-8
  0.00000
  0.55038  0.53489
  0.48462  0.50105  0.48990
  0.00000  0.46173  0.45833  0.00000
  0.46091  0.48896  0.48693  0.45649  0.47355
  0.47108  0.50152  0.50054  0.46467  0.46936  0.00000
  0.00000  0.50367  0.50465  0.00000  0.51807  0.56228  0.63841
  0.55301  0.57836  0.58286  0.56877  0.61200  0.65418  0.70015  0.74154
  0.63153  0.63775  0.64322  0.64999  0.67374  0.70398  0.73994  0.77479  0.80672


 Assembly:[3] H-9
  0.77785  0.78520  0.79146  0.79889  0.82589  0.85914  0.89866  0.94091  0.98982
  0.74013  0.76846  0.77421  0.75840  0.80242  0.84232  0.88966  0.93974  0.99960
  0.00000  0.74424  0.75015  0.00000  0.75903  0.79342  0.86853  0.93974  1.01172
  0.75930  0.79420  0.80594  0.78403  0.77300  0.00000  0.83293  0.93583  1.02229
  0.78364  0.82628  0.86619  0.88810  0.85171  0.80281  0.82667  0.93035  1.03285
  0.00000  0.83293  0.91666  0.00000  0.91353  0.83528  0.00000  0.91274  1.04224
  0.85875  0.88927  0.91666  0.93622  0.91157  0.88223  0.86540  0.95421  1.06024
  0.95695  0.93465  0.90492  0.86697  0.88653  0.88536  0.87401  0.96595  1.07315
  0.00000  0.96947  0.88418  0.00000  0.85484  0.85719  0.00000  0.94717  1.08136
  0.97847  0.95695  0.92761  0.89005  0.90961  0.90727  0.89553  0.98903  1.09662
  0.89905  0.93152  0.96243  0.98356  0.95695  0.92370  0.90453  0.99803  1.10679
  0.00000  0.89514  0.98395  0.00000  0.98082  0.89553  0.00000  0.97612  1.11384
  0.86501  0.91118  0.95265  0.97690  0.93543  0.87988  0.90687  1.01916  1.12949
  0.85875  0.89827  0.91040  0.88301  0.87010  0.00000  0.93622  1.04928  1.14357
  0.00000  0.86619  0.87205  0.00000  0.87910  0.91666  0.99999  1.07823  1.15883
  0.88888  0.92018  0.92526  0.90492  0.95265  0.99529  1.04615  1.10210  1.17213
  0.95656  0.96399  0.96947  0.97573  1.00077  1.03324  1.07432  1.12323  1.18856


 Assembly:[4] G-9
  0.86306
  0.88418 0.91626
  0.90492 0.94874 0.99764
  0.92487 0.98043 1.05632 0.00000
  0.94365 1.01133 1.09036 1.13144 1.13770
  0.96165 1.04733 0.00000 1.14435 1.16704 0.00000
  0.97299 1.04185 1.11423 1.12831 1.15374 1.19678 1.18778
  0.98434 1.05398 1.12675 1.13848 1.16470 1.20969 1.20147 1.21438
  0.99803 1.08488 0.00000 1.17565 1.20186 0.00000 1.23864 1.25233 0.00000
  1.00586 1.07667 1.15022 1.16274 1.18895 1.23394 1.22455 1.23825 1.27620 1.26133
  1.01485 1.08684 1.16196 1.17604 1.20225 1.24529 1.23551 1.24842 1.28715 1.27111 1.28324
  1.02581 1.11618 0.00000 1.21908 1.24099 0.00000 1.27033 1.28363 0.00000 1.30750 1.31806 0.00000
  1.03011 1.10093 1.18660 1.23003 1.23590 1.26759 1.25155 1.26289 1.30045 1.28598 1.29771 1.33840 1.33332
  1.03363 1.09349 1.17800 0.00000 1.25937 1.27346 1.25429 1.26485 1.30280 1.28754 1.30006 1.34505 1.35679 0.00000
  1.03637 1.08606 1.14318 1.21008 1.24764 0.00000 1.27541 1.28793 0.00000 1.31023 1.32158 0.00000 1.34310 1.32901 1.28637
  1.04028 1.08175 1.12323 1.16352 1.20147 1.24568 1.23864 1.25194 1.28637 1.27463 1.28402 1.31336 1.29185 1.27737 1.26250 1.25351
  1.04928 1.08723 1.12166 1.15492 1.18543 1.21203 1.22455 1.23746 1.25390 1.25898 1.26720 1.27698 1.27307 1.26759 1.26016 1.25742 1.26368
```

```
4B-2D Pin Power Uncertainties
-----------------------------
 Assembly:[1] H-8
  0.000%
  0.062%  0.064%
  0.066%  0.045%  0.066%
  0.000%  0.049%  0.047%  0.000%
  0.067%  0.046%  0.045%  0.048%  0.065%
  0.067%  0.046%  0.045%  0.048%  0.047%  0.000%
  0.000%  0.046%  0.045%  0.000%  0.045%  0.044%  0.056%
  0.063%  0.043%  0.043%  0.043%  0.042%  0.040%  0.039%  0.054%
  0.058%  0.041%  0.042%  0.041%  0.040%  0.039%  0.038%  0.038%  0.052%

 Assembly:[3] H-9
  0.053%  0.037%  0.037%  0.037%  0.037%  0.036%  0.035%  0.034%  0.033%
  0.054%  0.037%  0.039%  0.038%  0.037%  0.037%  0.035%  0.034%  0.033%
  0.000%  0.039%  0.039%  0.000%  0.038%  0.037%  0.035%  0.034%  0.032%
  0.054%  0.037%  0.037%  0.038%  0.037%  0.000%  0.036%  0.034%  0.033%
  0.052%  0.036%  0.035%  0.035%  0.037%  0.037%  0.036%  0.034%  0.034%
  0.000%  0.036%  0.035%  0.000%  0.035%  0.037%  0.000%  0.035%  0.033%
  0.051%  0.035%  0.035%  0.034%  0.035%  0.035%  0.035%  0.033%  0.032%
  0.049%  0.034%  0.035%  0.036%  0.036%  0.035%  0.036%  0.033%  0.032%
  0.000%  0.034%  0.036%  0.000%  0.036%  0.036%  0.000%  0.034%  0.032%
  0.048%  0.034%  0.034%  0.036%  0.034%  0.034%  0.035%  0.033%  0.031%
  0.050%  0.035%  0.034%  0.034%  0.034%  0.035%  0.035%  0.034%  0.031%
  0.000%  0.036%  0.035%  0.000%  0.034%  0.034%  0.000%  0.034%  0.032%
  0.049%  0.035%  0.034%  0.035%  0.035%  0.035%  0.036%  0.033%  0.031%
  0.052%  0.036%  0.035%  0.035%  0.036%  0.000%  0.035%  0.032%  0.030%
  0.000%  0.036%  0.036%  0.000%  0.036%  0.035%  0.033%  0.033%  0.031%
  0.051%  0.035%  0.034%  0.034%  0.034%  0.034%  0.033%  0.032%  0.030%
  0.049%  0.035%  0.034%  0.034%  0.034%  0.034%  0.031%  0.032%  0.031%

 Assembly:[4] G-9
  0.052%
  0.035%  0.049%
  0.035%  0.034%  0.047%
  0.034%  0.034%  0.033%  0.000%
  0.034%  0.034%  0.031%  0.032%  0.045%
  0.034%  0.034%  0.000%  0.032%  0.031%  0.000%
  0.034%  0.033%  0.032%  0.031%  0.031%  0.031%  0.043%
  0.034%  0.033%  0.032%  0.031%  0.031%  0.030%  0.031%  0.043%
  0.033%  0.031%  0.000%  0.031%  0.030%  0.000%  0.030%  0.029%  0.000%
  0.034%  0.032%  0.031%  0.031%  0.030%  0.031%  0.030%  0.030%  0.029%  0.042%
  0.033%  0.031%  0.031%  0.030%  0.030%  0.030%  0.030%  0.030%  0.029%  0.029%  0.041%
  0.033%  0.032%  0.000%  0.029%  0.030%  0.000%  0.030%  0.029%  0.000%  0.029%  0.029%  0.000%
  0.032%  0.031%  0.031%  0.030%  0.030%  0.030%  0.030%  0.030%  0.029%  0.030%  0.029%  0.029%  0.041%
  0.032%  0.032%  0.030%  0.000%  0.030%  0.030%  0.030%  0.030%  0.029%  0.029%  0.029%  0.029%  0.028%  0.000%
  0.032%  0.031%  0.031%  0.030%  0.030%  0.000%  0.029%  0.029%  0.000%  0.030%  0.028%  0.000%  0.029%  0.029%  0.042%
  0.032%  0.032%  0.031%  0.031%  0.030%  0.030%  0.030%  0.029%  0.029%  0.029%  0.029%  0.029%  0.029%  0.029%  0.029%  0.042%
  0.033%  0.032%  0.032%  0.031%  0.030%  0.030%  0.030%  0.030%  0.030%  0.030%  0.029%  0.030%  0.029%  0.029%  0.029%  0.030%  0.041%
```

```
4C-2D Pin Powers
----------------
 Assembly:[1] H-8
  0.00000
  0.48203  0.46747
  0.42249  0.43752  0.42838
  0.00000  0.40322  0.40023  0.00000
  0.40467  0.42951  0.42908  0.40133  0.41927
  0.41684  0.44529  0.44423  0.41244  0.41970  0.00000
  0.00000  0.45495  0.45667  0.00000  0.47418  0.52269  0.60186
  0.51115  0.53470  0.53981  0.52925  0.57384  0.61831  0.66898  0.71506
  0.59409  0.60041  0.60688  0.61513  0.64146  0.67475  0.71384  0.75215  0.78893


 Assembly:[3] H-9
  0.74300  0.74987  0.75745  0.76702  0.79599  0.83132  0.87449  0.92002  0.97301
  0.71502  0.74304  0.74972  0.73508  0.78115  0.82268  0.87174  0.92473  0.98675
  0.00000  0.72683  0.73303  0.00000  0.74422  0.77982  0.85644  0.92983  1.00323
  0.74732  0.78135  0.79364  0.77299  0.76235  0.00000  0.82504  0.92944  1.01736
  0.77354  0.81719  0.85722  0.88077  0.84545  0.79756  0.82150  0.92591  1.03031
  0.00000  0.82700  0.91021  0.00000  0.90942  0.83210  0.00000  0.91099  1.04209
  0.85487  0.88627  0.91374  0.93376  0.90864  0.88077  0.86586  0.95574  1.06171
  0.95574  0.93376  0.90354  0.86546  0.88705  0.88548  0.87528  0.96869  1.07702
  0.00000  0.96987  0.88548  0.00000  0.85604  0.85958  0.00000  0.95221  1.08762
  0.98047  0.95809  0.93023  0.89294  0.91296  0.91021  0.89961  0.99420  1.10371
  0.90197  0.93611  0.96594  0.98832  0.96123  0.92983  0.91060  1.00441  1.11509
  0.00000  0.89961  0.98871  0.00000  0.98635  0.90079  0.00000  0.98361  1.12294
  0.86978  0.91649  0.95927  0.98282  0.94239  0.88705  0.91453  1.02757  1.13943
  0.86507  0.90393  0.91727  0.88901  0.87685  0.00000  0.94475  1.05818  1.15513
  0.00000  0.87253  0.87802  0.00000  0.88587  0.92434  1.00833  1.08801  1.17044
  0.89647  0.92709  0.93258  0.91256  0.96084  1.00480  1.05543  1.11274  1.18496
  0.96437  0.97183  0.97811  0.98439  1.00912  1.04248  1.08487  1.13433  1.20027


 Assembly:[4] G-9
  0.85330
  0.87645 0.91139
  0.90000 0.94514 0.99617
  0.92355 0.98007 1.05779 0.00000
  0.94318 1.01265 1.09233 1.13629 1.14375
  0.96320 1.04955 0.00000 1.15120 1.17515 0.00000
  0.97536 1.04601 1.12020 1.13590 1.16219 1.20576 1.19870
  0.98910 1.06014 1.13354 1.14846 1.17515 1.22068 1.21283 1.22774
  1.00402 1.09272 0.00000 1.18457 1.21204 0.00000 1.25168 1.26660 0.00000
  1.01304 1.08526 1.16062 1.17358 1.20105 1.24737 1.23795 1.25365 1.29250 1.27877
  1.02364 1.09743 1.17318 1.18810 1.21400 1.25953 1.24972 1.26464 1.30310 1.28897 1.29996
  1.03502 1.12687 0.00000 1.23167 1.25522 0.00000 1.28622 1.29996 0.00000 1.32469 1.33725 0.00000
  1.03973 1.11235 1.19948 1.24423 1.25129 1.28348 1.26699 1.27994 1.31802 1.30389 1.31684 1.35923 1.35334
  1.04327 1.10567 1.19006 0.00000 1.27445 1.28976 1.27092 1.28230 1.32155 1.30664 1.31998 1.36669 1.37729 0.00000
  1.04719 1.09782 1.15631 1.22303 1.26424 0.00000 1.29211 1.30506 0.00000 1.32940 1.34157 0.00000 1.36433 1.34981 1.30781
  1.05229 1.09390 1.13550 1.17868 1.21675 1.26307 1.25600 1.26974 1.30585 1.29250 1.30349 1.33490 1.31252 1.29761 1.28308 1.27406
  1.06171 1.09939 1.13472 1.16965 1.19987 1.22735 1.23991 1.25522 1.27170 1.27759 1.28662 1.29721 1.29290 1.28819 1.28073 1.27798 1.28505
```

```
4C-2D Pin Power Uncertainties
-----------------------------
 Assembly:[1] H-8
  0.000%
  0.067%  0.069%
  0.071%  0.050%  0.071%
  0.000%  0.051%  0.052%  0.000%
  0.071%  0.050%  0.049%  0.050%  0.070%
  0.071%  0.048%  0.048%  0.050%  0.050%  0.000%
  0.000%  0.048%  0.048%  0.000%  0.048%  0.046%  0.060%
  0.064%  0.045%  0.045%  0.045%  0.043%  0.041%  0.040%  0.056%
  0.062%  0.042%  0.042%  0.042%  0.042%  0.040%  0.039%  0.038%  0.053%

 Assembly:[3] H-9
  0.055%  0.039%  0.038%  0.038%  0.038%  0.036%  0.036%  0.035%  0.034%
  0.055%  0.040%  0.039%  0.039%  0.037%  0.037%  0.035%  0.035%  0.034%
  0.000%  0.039%  0.039%  0.000%  0.039%  0.039%  0.036%  0.034%  0.033%
  0.054%  0.038%  0.037%  0.037%  0.039%  0.000%  0.035%  0.035%  0.034%
  0.054%  0.036%  0.036%  0.036%  0.036%  0.037%  0.036%  0.034%  0.033%
  0.000%  0.037%  0.035%  0.000%  0.034%  0.037%  0.000%  0.036%  0.033%
  0.051%  0.035%  0.035%  0.035%  0.035%  0.036%  0.036%  0.034%  0.032%
  0.049%  0.035%  0.035%  0.035%  0.036%  0.035%  0.035%  0.034%  0.032%
  0.000%  0.035%  0.036%  0.000%  0.035%  0.036%  0.000%  0.034%  0.031%
  0.048%  0.034%  0.035%  0.035%  0.035%  0.035%  0.035%  0.034%  0.032%
  0.050%  0.035%  0.035%  0.034%  0.034%  0.035%  0.034%  0.033%  0.032%
  0.000%  0.035%  0.034%  0.000%  0.034%  0.035%  0.000%  0.033%  0.031%
  0.050%  0.034%  0.035%  0.034%  0.034%  0.035%  0.035%  0.033%  0.031%
  0.051%  0.034%  0.035%  0.035%  0.035%  0.000%  0.035%  0.033%  0.031%
  0.000%  0.035%  0.035%  0.000%  0.035%  0.035%  0.033%  0.031%  0.030%
  0.050%  0.035%  0.035%  0.035%  0.033%  0.033%  0.032%  0.032%  0.030%
  0.048%  0.034%  0.034%  0.034%  0.033%  0.033%  0.031%  0.032%  0.030%

 Assembly:[4] G-9
  0.049%
  0.035%  0.050%
  0.034%  0.034%  0.048%
  0.035%  0.034%  0.032%  0.000%
  0.035%  0.034%  0.032%  0.031%  0.044%
  0.034%  0.032%  0.000%  0.030%  0.030%  0.000%
  0.034%  0.033%  0.031%  0.031%  0.032%  0.030%  0.043%
  0.034%  0.033%  0.031%  0.031%  0.030%  0.030%  0.030%  0.043%
  0.034%  0.032%  0.000%  0.030%  0.030%  0.000%  0.029%  0.030%  0.000%
  0.033%  0.032%  0.031%  0.031%  0.030%  0.030%  0.030%  0.030%  0.029%  0.043%
  0.033%  0.031%  0.031%  0.031%  0.030%  0.030%  0.030%  0.030%  0.030%  0.030%  0.041%
  0.033%  0.031%  0.000%  0.031%  0.029%  0.000%  0.029%  0.029%  0.000%  0.029%  0.029%  0.000%
  0.032%  0.032%  0.030%  0.030%  0.030%  0.030%  0.030%  0.029%  0.029%  0.029%  0.029%  0.029%  0.040%
  0.032%  0.031%  0.031%  0.000%  0.029%  0.030%  0.030%  0.030%  0.029%  0.029%  0.029%  0.028%  0.029%  0.000%
  0.032%  0.032%  0.031%  0.030%  0.030%  0.000%  0.029%  0.029%  0.000%  0.029%  0.029%  0.000%  0.030%  0.029%  0.042%
  0.033%  0.032%  0.031%  0.030%  0.030%  0.029%  0.030%  0.029%  0.029%  0.029%  0.029%  0.028%  0.029%  0.030%  0.029%  0.042%
  0.032%  0.032%  0.031%  0.031%  0.030%  0.030%  0.030%  0.030%  0.030%  0.029%  0.030%  0.029%  0.029%  0.029%  0.030%  0.030%  0.042%
```

Problem 4-2D ENDF/B-VI.8 Power Results

```
4A-2D Assembly Powers
---------------------
   0.99842
   0.92249 1.07790
```

```
4A-2D Assembly Power Uncertainties
----------------------------------
   0.069%
   0.067%  0.061%
```

```
4B-2D Assembly Powers
---------------------
   0.57203
   0.92652 1.18048
```

```
4B-2D Assembly Powers
---------------------
   0.091%
   0.067%  0.060%
```

```
No 4C-2D Results
```

```
4A-2D Pin Powers
----------------
 Assembly:[1,1] H-8
  0.00000
  1.07282 1.05061
  1.07358 1.04831 1.04831
  0.00000 1.06746 1.06975 0.00000
  1.06286 1.04065 1.04219 1.06784 1.05291
  1.05061 1.02917 1.03070 1.06018 1.06133 0.00000
  0.00000 1.02993 1.03070 0.00000 1.03529 1.01845 0.97480
  0.99126 0.97365 0.97403 0.99318 0.97135 0.95834 0.94302 0.92885
  0.92005 0.91928 0.91928 0.92273 0.92005 0.91813 0.91584 0.91545 0.91660

 Assembly:[1,2] H-9
  1.00773 1.01347 1.01309 1.01270 1.02113 1.03338 1.04640 1.06095 1.08507
  0.89248 0.92273 0.92503 0.89708 0.93307 0.96063 0.99165 1.02266 1.06439
  0.00000 0.84386 0.84730 0.00000 0.84079 0.86913 0.93460 0.99394 1.05291
  0.82433 0.86453 0.87487 0.84271 0.82471 0.00000 0.87142 0.96638 1.04257
  0.83084 0.87449 0.91201 0.93307 0.88789 0.82816 0.84424 0.94072 1.03376
  0.00000 0.85841 0.94494 0.00000 0.93422 0.84539 0.00000 0.90627 1.02687
  0.86951 0.90014 0.92809 0.94570 0.91507 0.87946 0.85419 0.93536 1.03070
  0.95489 0.93077 0.90090 0.86147 0.87793 0.86951 0.85266 0.93651 1.03032
  0.00000 0.95451 0.86759 0.00000 0.83199 0.83084 0.00000 0.90665 1.02802
  0.95183 0.92885 0.89899 0.85955 0.87678 0.86874 0.85151 0.93766 1.03376
  0.86491 0.89669 0.92388 0.94111 0.91316 0.87946 0.85573 0.93766 1.03683
  0.00000 0.85151 0.93766 0.00000 0.92809 0.84271 0.00000 0.91086 1.03606
  0.81667 0.86109 0.90129 0.92235 0.88023 0.82318 0.84347 0.94532 1.04410
  0.80672 0.84462 0.85534 0.82739 0.81208 0.00000 0.86683 0.96867 1.05252
  0.00000 0.80901 0.81399 0.00000 0.81552 0.84960 0.92388 0.99318 1.06324
  0.82892 0.85917 0.86223 0.84041 0.88406 0.92235 0.96446 1.01309 1.07435
  0.89018 0.89899 0.90359 0.90627 0.92809 0.95566 0.98897 1.03223 1.08928

 Assembly:[2,2] G-9
  0.91967
  0.92196 0.93881
  0.92541 0.95604 0.99394
  0.93039 0.97289 1.03836 0.00000
  0.93498 0.99126 1.05942 1.08851 1.08354
  0.93919 1.01538 0.00000 1.09081 1.10383 0.00000
  0.93919 0.99739 1.06095 1.06554 1.08047 1.11417 1.09732
  0.93996 1.00045 1.06133 1.06516 1.08392 1.11723 1.10230 1.11034
  0.94455 1.02151 0.00000 1.09311 1.11034 0.00000 1.13025 1.13752 0.00000
  0.94340 1.00466 1.06822 1.07358 1.09043 1.12642 1.11302 1.11953 1.14863 1.13178
  0.94532 1.00734 1.07282 1.07818 1.09655 1.13178 1.11800 1.12374 1.15322 1.13714 1.14020
  0.94953 1.02917 0.00000 1.11455 1.12986 0.00000 1.14518 1.15092 0.00000 1.16394 1.16892 0.00000
  0.94915 1.01117 1.08583 1.11838 1.12068 1.14365 1.12297 1.12986 1.15973 1.14212 1.14863 1.18308 1.17466
  0.94800 0.99930 1.07128 0.00000 1.13867 1.14441 1.12259 1.12642 1.15896 1.14097 1.14748 1.18653 1.19380 0.00000
  0.94723 0.98858 1.03683 1.09502 1.12565 0.00000 1.13982 1.14671 0.00000 1.15973 1.16585 0.00000 1.17926 1.16471 1.12489
  0.94953 0.98399 1.01692 1.04984 1.07971 1.11608 1.10613 1.11302 1.14173 1.12565 1.13063 1.15513 1.13331 1.11876 1.10345 1.09426
  0.95719 0.98743 1.01424 1.04219 1.06401 1.08507 1.09005 1.09923 1.10957 1.11187 1.11646 1.12259 1.11723 1.10727 1.10077 1.09809 1.10115
```

```
4A-2D Pin Power Uncertainties
-----------------------------
 Assembly:[1,1] H-8
  0.000%
  0.085%  0.090%
  0.085%  0.064%  0.090%
  0.000%  0.064%  0.064%  0.000%
  0.085%  0.064%  0.064%  0.060%  0.090%
  0.085%  0.064%  0.060%  0.060%  0.064%  0.000%
  0.000%  0.064%  0.064%  0.000%  0.064%  0.064%  0.090%
  0.088%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.090%
  0.092%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.090%

 Assembly:[1,2] H-9
  0.085%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.060%
  0.092%  0.064%  0.064%  0.067%  0.064%  0.064%  0.064%  0.064%  0.060%
  0.000%  0.071%  0.071%  0.000%  0.071%  0.067%  0.064%  0.064%  0.064%
  0.099%  0.064%  0.067%  0.064%  0.071%  0.000%  0.064%  0.064%  0.064%
  0.095%  0.064%  0.064%  0.064%  0.067%  0.071%  0.071%  0.064%  0.057%
  0.000%  0.064%  0.064%  0.000%  0.064%  0.067%  0.000%  0.064%  0.060%
  0.095%  0.064%  0.064%  0.064%  0.064%  0.067%  0.067%  0.064%  0.064%
  0.092%  0.064%  0.064%  0.067%  0.067%  0.067%  0.071%  0.064%  0.064%
  0.000%  0.064%  0.067%  0.000%  0.071%  0.071%  0.000%  0.064%  0.064%
  0.092%  0.064%  0.064%  0.064%  0.067%  0.067%  0.071%  0.064%  0.057%
  0.099%  0.064%  0.067%  0.064%  0.064%  0.064%  0.067%  0.064%  0.064%
  0.000%  0.071%  0.064%  0.000%  0.064%  0.067%  0.000%  0.064%  0.064%
  0.095%  0.067%  0.067%  0.064%  0.064%  0.071%  0.067%  0.064%  0.060%
  0.099%  0.071%  0.067%  0.071%  0.071%  0.000%  0.067%  0.064%  0.064%
  0.000%  0.071%  0.071%  0.000%  0.071%  0.071%  0.064%  0.064%  0.060%
  0.099%  0.064%  0.071%  0.071%  0.064%  0.064%  0.064%  0.064%  0.064%
  0.092%  0.064%  0.064%  0.067%  0.064%  0.064%  0.064%  0.064%  0.057%

 Assembly:[2,2] G-9
  0.090%
  0.064%  0.090%
  0.064%  0.064%  0.090%
  0.064%  0.064%  0.064%  0.000%
  0.064%  0.064%  0.064%  0.057%  0.080%
  0.064%  0.064%  0.000%  0.060%  0.057%  0.000%
  0.064%  0.064%  0.064%  0.057%  0.064%  0.057%  0.080%
  0.064%  0.064%  0.057%  0.057%  0.060%  0.057%  0.064%  0.080%
  0.064%  0.064%  0.000%  0.057%  0.060%  0.000%  0.057%  0.057%  0.000%
  0.064%  0.064%  0.064%  0.064%  0.064%  0.060%  0.057%  0.057%  0.057%  0.080%
  0.064%  0.064%  0.064%  0.064%  0.064%  0.057%  0.057%  0.060%  0.057%  0.057%  0.080%
  0.064%  0.064%  0.000%  0.057%  0.057%  0.000%  0.057%  0.057%  0.000%  0.057%  0.057%  0.000%
  0.064%  0.064%  0.060%  0.060%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.080%
  0.064%  0.064%  0.060%  0.000%  0.060%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.000%
  0.064%  0.064%  0.064%  0.057%  0.057%  0.000%  0.057%  0.057%  0.000%  0.057%  0.057%  0.000%  0.057%  0.057%  0.080%
  0.064%  0.064%  0.060%  0.064%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.080%
  0.064%  0.064%  0.060%  0.060%  0.064%  0.060%  0.064%  0.060%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.090%
```

```
4B-2D Pin Powers
----------------
 Assembly:[1,1] H-8
  0.00000
  0.55471 0.53764
  0.48621 0.50384 0.49317
  0.00000 0.46358 0.45871 0.00000
  0.46170 0.49101 0.48967 0.45792 0.47594
  0.47346 0.50329 0.50226 0.46532 0.46898 0.00000
  0.00000 0.50411 0.50612 0.00000 0.51808 0.56286 0.64120
  0.55530 0.58072 0.58552 0.56994 0.61444 0.65615 0.70289 0.74405
  0.63419 0.63978 0.64604 0.65284 0.67629 0.70604 0.74200 0.77651 0.80661

 Assembly:[1,2] H-9
  0.78115 0.78812 0.79481 0.80110 0.82864 0.86288 0.90144 0.94393 0.99311
  0.74224 0.77088 0.77671 0.76034 0.80425 0.84517 0.89121 0.94157 1.00216
  0.00000 0.74495 0.75101 0.00000 0.76057 0.79481 0.87035 0.94157 1.01397
  0.76081 0.79520 0.80858 0.78438 0.77324 0.00000 0.83337 0.93724 1.02341
  0.78316 0.82825 0.86760 0.89121 0.85304 0.80228 0.82510 0.92977 1.03364
  0.00000 0.83376 0.91796 0.00000 0.91560 0.83494 0.00000 0.91324 1.04230
  0.85934 0.89121 0.91757 0.93842 0.91442 0.88334 0.86563 0.95455 1.06000
  0.95849 0.93724 0.90616 0.86760 0.88806 0.88452 0.87429 0.96518 1.07220
  0.00000 0.97147 0.88452 0.00000 0.85422 0.85658 0.00000 0.94669 1.08007
  0.98170 0.95888 0.92741 0.89003 0.90970 0.90694 0.89317 0.98879 1.09620
  0.89868 0.93291 0.96321 0.98564 0.95770 0.92426 0.90419 0.99823 1.10643
  0.00000 0.89514 0.98603 0.00000 0.98092 0.89396 0.00000 0.97541 1.11312
  0.86484 0.91167 0.95377 0.97934 0.93567 0.87901 0.90537 1.01790 1.12650
  0.85815 0.89789 0.91088 0.88216 0.86878 0.00000 0.93409 1.04820 1.14303
  0.00000 0.86563 0.87153 0.00000 0.87743 0.91521 0.99862 1.07692 1.15719
  0.88766 0.92072 0.92465 0.90419 0.95337 0.99548 1.04663 1.10171 1.17175
  0.95652 0.96439 0.96990 0.97541 0.99980 1.03325 1.07496 1.12217 1.18867

 Assembly:[2,2] G-9
  0.86406
  0.88530 0.91521
  0.90694 0.94905 0.99941
  0.92583 0.98131 1.05804 0.00000
  0.94550 1.01161 1.09148 1.13280 1.13870
  0.96321 1.04781 0.00000 1.14539 1.16781 0.00000
  0.97265 1.04269 1.11627 1.12965 1.15286 1.19732 1.18670
  0.98406 1.05450 1.12729 1.13870 1.16427 1.20873 1.20047 1.21424
  0.99626 1.08676 0.00000 1.17608 1.20244 0.00000 1.23706 1.25162 0.00000
  1.00492 1.07732 1.15050 1.16231 1.18827 1.23352 1.22329 1.23510 1.27523 1.25910
  1.01594 1.08676 1.16270 1.17529 1.20087 1.24690 1.23313 1.24533 1.28625 1.26933 1.28113
  1.02617 1.11666 0.00000 1.21936 1.24061 0.00000 1.26933 1.28192 0.00000 1.30592 1.31576 0.00000
  1.03049 1.10211 1.18749 1.23156 1.23549 1.26618 1.24926 1.25989 1.29845 1.28310 1.29569 1.33858 1.33228
  1.03364 1.09306 1.17726 0.00000 1.25871 1.27287 1.25280 1.26185 1.30081 1.28546 1.29766 1.34369 1.35432 0.00000
  1.03640 1.08519 1.14145 1.20952 1.24769 0.00000 1.27366 1.28585 0.00000 1.30907 1.32048 0.00000 1.34055 1.32599 1.28271
  1.03994 1.08007 1.12178 1.16152 1.19969 1.24375 1.23588 1.24848 1.28389 1.27287 1.28035 1.31064 1.28782 1.27248 1.25949 1.25123
  1.04938 1.08519 1.12138 1.15286 1.18277 1.20873 1.22054 1.23510 1.25044 1.25516 1.26461 1.27405 1.27051 1.26421 1.25713 1.25320 1.25989
```

```
4B-2D Pin Power Uncertainties
```

```
------------------------------
 Assembly:[1,1] H-8
  0.000%
  0.120%  0.120%
  0.127%  0.088%  0.130%
  0.000%  0.092%  0.092%  0.000%
  0.127%  0.085%  0.085%  0.092%  0.130%
  0.127%  0.088%  0.085%  0.092%  0.088%  0.000%
  0.000%  0.088%  0.088%  0.000%  0.085%  0.081%  0.110%
  0.120%  0.078%  0.081%  0.085%  0.078%  0.078%  0.074%  0.100%
  0.110%  0.078%  0.078%  0.078%  0.078%  0.074%  0.071%  0.071%  0.100%

 Assembly:[1,2] H-9
  0.099%  0.071%  0.071%  0.071%  0.071%  0.067%  0.064%  0.064%  0.064%
  0.103%  0.071%  0.071%  0.071%  0.071%  0.071%  0.067%  0.064%  0.064%
  0.000%  0.071%  0.071%  0.000%  0.071%  0.071%  0.067%  0.064%  0.064%
  0.103%  0.071%  0.071%  0.071%  0.071%  0.000%  0.071%  0.064%  0.064%
  0.099%  0.071%  0.071%  0.071%  0.071%  0.071%  0.071%  0.064%  0.064%
  0.000%  0.071%  0.064%  0.000%  0.064%  0.071%  0.000%  0.067%  0.064%
  0.099%  0.067%  0.064%  0.064%  0.064%  0.064%  0.071%  0.064%  0.064%
  0.092%  0.064%  0.064%  0.067%  0.067%  0.071%  0.071%  0.064%  0.064%
  0.000%  0.064%  0.067%  0.000%  0.071%  0.071%  0.000%  0.064%  0.064%
  0.092%  0.067%  0.064%  0.067%  0.064%  0.064%  0.064%  0.064%  0.060%
  0.095%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.060%
  0.000%  0.067%  0.064%  0.000%  0.064%  0.064%  0.000%  0.064%  0.060%
  0.095%  0.064%  0.064%  0.064%  0.064%  0.067%  0.064%  0.064%  0.060%
  0.099%  0.064%  0.064%  0.064%  0.067%  0.000%  0.064%  0.064%  0.057%
  0.000%  0.067%  0.067%  0.000%  0.071%  0.064%  0.064%  0.064%  0.057%
  0.092%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.060%  0.060%
  0.092%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.057%

 Assembly:[2,2] G-9
  0.090%
  0.064%  0.090%
  0.064%  0.064%  0.090%
  0.064%  0.064%  0.060%  0.000%
  0.064%  0.064%  0.060%  0.060%  0.080%
  0.064%  0.064%  0.000%  0.057%  0.057%  0.000%
  0.064%  0.064%  0.057%  0.060%  0.057%  0.057%  0.080%
  0.064%  0.060%  0.057%  0.057%  0.057%  0.057%  0.057%  0.080%
  0.064%  0.060%  0.000%  0.057%  0.057%  0.000%  0.057%  0.057%  0.000%
  0.064%  0.064%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.080%
  0.064%  0.064%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.080%
  0.064%  0.060%  0.000%  0.057%  0.057%  0.000%  0.057%  0.057%  0.000%  0.057%  0.057%  0.000%
  0.064%  0.060%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.080%
  0.064%  0.057%  0.057%  0.000%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.053%  0.000%
  0.064%  0.060%  0.060%  0.057%  0.057%  0.000%  0.057%  0.057%  0.000%  0.057%  0.057%  0.000%  0.057%  0.057%  0.080%
  0.060%  0.060%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.080%
  0.064%  0.060%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.080%

No 4C-2D results for ENDF/B-VI data.
```

APPENDIX I – PROBLEM REF1-2D DATA AND RESULTS

The following are the ENDF/B-VII.0 isotopics and results for Problem REF1-2D, in ASCII form.

```
mixture = fuel (2.11%)
  8016  4.57591E-02                        Mixture = pyrex
 92234  4.04814E-06                          5010  9.63266E-04
 92235  4.88801E-04                          5011  3.90172E-03
 92236  2.23756E-06                          8016  4.67761E-02
 92238  2.23844E-02                         14028  1.81980E-02
                                            14029  9.24474E-04
mixture = fuel (3.10%)                      14030  6.10133E-04
  8016  4.57642E-02
 92234  6.11864E-06                        mixture = stainless steel
 92235  7.18132E-04                          6000  3.20895E-04
 92236  3.29861E-06                         14028  1.58197E-03
 92238  2.21546E-02                         14029  8.03653E-05
                                            14030  5.30394E-05
mixture = gap                               15031  6.99938E-05
  2004  2.68714E-05                         24050  7.64915E-04
                                            24052  1.47506E-02
mixture =  cladding (zircaloy-4)            24053  1.67260E-03
 24050  3.30121E-06                         24054  4.16346E-04
 24052  6.36606E-05                         25055  1.75387E-03
 24053  7.21860E-06                         26054  3.44776E-03
 24054  1.79686E-06                         26056  5.41225E-02
 26054  8.68307E-06                         26057  1.24992E-03
 26056  1.36306E-04                         26058  1.66342E-04
 26057  3.14789E-06                         28058  5.30854E-03
 26058  4.18926E-07                         28060  2.04484E-03
 40090  2.18865E-02                         28061  8.88879E-05
 40091  4.77292E-03                         28062  2.83413E-04
 40092  7.29551E-03                         28064  7.21770E-05
 40094  7.39335E-03
 40096  1.19110E-03
 50112  4.68066E-06
 50114  3.18478E-06
 50115  1.64064E-06
 50116  7.01616E-05
 50117  3.70592E-05
 50118  1.16872E-04
 50119  4.14504E-05
 50120  1.57212E-04
 50122  2.23417E-05
 50124  2.79392E-05
 72174  3.54138E-09
 72176  1.16423E-07
 72177  4.11686E-07
 72178  6.03806E-07
 72179  3.01460E-07
 72180  7.76449E-07

mixture = moderator
  1001  4.96224E-02
  5010  1.07070E-05
  5011  4.30971E-05
  8016  2.48112E-02
```

Problem REF1-2D ENDF/B-VII.0 Eigenvalue Result = 0.993677 +/- 0.000021

Problem REF1-2D ENDF/B-VII.0 Power Results

Radial Assembly Powers

 1.09977 0.85895   0.086% 0.100%
 1.08126 0.99809   0.087% 0.091%
 1.14704 0.94020   0.085% 0.095%

Radial Pin Powers

 Assembly:[1,1] B-8
  0.00000 1.20743 1.20330 0.00000 1.18266 1.17028 0.00000 1.08875 1.00351
  1.20536 1.17956 1.17647 1.19608 1.15996 1.14344 1.13519 1.06708 1.00000
  1.20536 1.17956 1.17647 1.19608 1.16202 1.14551 1.13622 1.06604 0.99360
  0.00000 1.19814 1.19711 0.00000 1.18988 1.17337 0.00000 1.08359 0.99391
  1.19195 1.16718 1.16718 1.19195 1.17131 1.17337 1.13828 1.05985 0.98844
  1.17750 1.15273 1.15376 1.18266 1.17853 0.00000 1.11661 1.04025 0.98122
  0.00000 1.15067 1.14964 0.00000 1.14757 1.12074 1.06604 1.01682 0.97317
  1.10216 1.08049 1.08256 1.09804 1.07120 1.04747 1.02332 0.99566 0.96285
  1.01393 1.01001 1.00867 1.01083 1.00144 0.99143 0.98080 0.96326 0.94355

 Assembly:[2,1] A-8
  1.21362 1.00000 1.08978 0.95779 0.00000 0.88008 0.92394 0.00000 0.84427 0.72972 0.00000 0.63158 0.64210 0.00000 0.53736 0.44210
  1.25799 1.17647 1.13932 1.06295 0.99154 0.92012 0.91218 0.90289 0.88462 0.82157 0.75211 0.68452 0.65800 0.62786 0.59040 0.51857 0.43849
  1.24148 1.12590 1.03612 1.03158 1.02569 1.01207 0.94819 0.88049 0.80939 0.79463 0.77719 0.75036 0.68720 0.61599 0.54056 0.49443 0.42982
  1.23013 1.08256 0.00000 1.00598 1.05985 0.00000 0.98163 0.85758 0.00000 0.77028 0.79989 0.00000 0.71455 0.60794 0.00000 0.47275 0.42693
  1.23839 1.12900 1.05469 1.08668 1.05572 1.03054 0.96316 0.89339 0.82188 0.80609 0.78854 0.76594 0.70960 0.65366 0.55480 0.50031 0.43478
  1.24355 1.16615 1.14964 0.00000 1.05985 0.95098 0.93942 0.92817 0.90980 0.84396 0.77482 0.70691 0.70567 0.00000 0.60794 0.52281 0.44530
  1.24355 1.17440 1.13932 1.11971 0.99752 0.00000 0.91383 0.96408 0.00000 0.88287 0.76243 0.00000 0.66419 0.67069 0.60371 0.53261 0.45119
  1.24252 1.17750 1.13519 1.09597 1.03085 0.95655 0.96068 0.96377 0.95645 0.88029 0.79948 0.71579 0.69288 0.66089 0.60567 0.53901 0.45820
  1.24045 1.18679 1.15067 1.11558 1.07740 1.03612 1.01176 0.98297 0.95253 0.89835 0.84056 0.77719 0.73116 0.67781 0.61961 0.55119 0.46790

 Assembly:[1,2] B-9
  1.24974 1.25284 1.25180 1.24561 1.24974 1.25180 1.25490 1.25077 1.24871
  1.08875 1.12177 1.12177 1.08978 1.12280 1.14448 1.16821 1.18782 1.20330
  0.00000 1.01465 1.01269 0.00000 0.99979 1.02889 1.09494 1.14138 1.17440
  0.98029 1.01692 1.01094 0.96006 0.95273 0.00000 1.01414 1.10526 1.15789
  0.97028 1.00516 0.99958 0.95211 0.96821 0.94613 0.98018 1.07327 1.14551
  0.00000 0.97244 0.96708 0.00000 0.94943 0.94943 0.00000 1.03302 1.13519
  1.01197 1.03168 1.01506 0.96501 0.99546 0.99938 0.98545 1.06501 1.14035
  1.12177 1.08772 1.03199 0.97234 1.00051 1.00454 0.98689 1.06604 1.14138
  0.00000 1.12487 1.01579 0.00000 0.96801 0.97069 0.00000 1.03715 1.13932
  1.12487 1.09081 1.03715 0.97667 1.00299 1.00877 0.99339 1.07017 1.14654
  1.01950 1.04128 1.02043 0.97327 1.00165 1.00753 0.99391 1.07224 1.14860
  0.00000 0.98307 0.97884 0.00000 0.96089 0.96140 0.00000 1.04747 1.15067
  0.98545 1.01940 1.01610 0.96666 0.98328 0.96192 0.99360 1.09081 1.16615
  0.99639 1.03715 1.03137 0.97822 0.97028 0.00000 1.03405 1.12693 1.18060
  0.00000 1.03715 1.03509 0.00000 1.01981 1.05263 1.11971 1.16924 1.20330
  1.11971 1.15170 1.14964 1.11661 1.15376 1.17750 1.20227 1.22084 1.23529
  1.28379 1.28895 1.28689 1.28379 1.28792 1.28999 1.29205 1.29205 1.28792

```
Assembly:[2,2] A-9
 1.22084 1.18369 1.15996 1.13932 1.11145 1.08668 1.05160 1.01362 0.97750 0.92538 0.87162 0.82095 0.76130 0.69886 0.63426 0.56109 0.47482
 1.19711 1.17647 1.16718 1.16305 1.15376 1.15273 1.08978 1.05057 1.02858 0.95913 0.90588 0.87224 0.79350 0.72157 0.64468 0.56728 0.47895
 1.18679 1.18679 1.20330 1.23323 1.22807 0.00000 1.14757 1.10216 0.00000 1.00763 0.95376 0.00000 0.84747 0.77028 0.67141 0.58008 0.48565
 1.18782 1.20227 1.25903 0.00000 1.25387 1.21362 1.13725 1.09288 1.07430 0.99783 0.94613 0.92064 0.86470 0.00000 0.70991 0.59680 0.49474
 1.18988 1.22394 1.28173 1.28586 1.23736 1.22188 1.14757 1.10216 1.08462 1.00743 0.95758 0.92951 0.85655 0.80681 0.72590 0.61259 0.50237
 1.19401 1.25696 0.00000 1.28173 1.25593 0.00000 1.18472 1.14035 0.00000 1.04334 0.98761 0.00000 0.87348 0.80825 0.00000 0.63405 0.51063
 1.19401 1.22910 1.27657 1.24355 1.22188 1.22497 1.15789 1.11558 1.09804 1.02002 0.96605 0.93478 0.85088 0.78204 0.72642 0.62301 0.51104
 1.19195 1.23013 1.27863 1.24148 1.22291 1.22807 1.15996 1.11868 1.10216 1.02353 0.97100 0.93663 0.85242 0.78524 0.72982 0.62322 0.51259
 1.20020 1.26212 0.00000 1.27554 1.25799 0.00000 1.19504 1.14860 0.00000 1.05366 1.00072 0.00000 0.87729 0.80691 0.00000 0.64066 0.51661
 1.19814 1.23736 1.28276 1.24664 1.22910 1.23323 1.16718 1.12487 1.10732 1.02962 0.97461 0.94200 0.85800 0.78896 0.73323 0.62580 0.51599
 1.20124 1.23839 1.28586 1.25387 1.23116 1.23839 1.16821 1.12693 1.10939 1.03096 0.97812 0.94448 0.85892 0.79288 0.73467 0.62807 0.51651
 1.20846 1.27347 0.00000 1.30237 1.27554 0.00000 1.20020 1.15789 0.00000 1.06088 1.00330 0.00000 0.88865 0.81919 0.00000 0.64386 0.51816
 1.21156 1.24458 1.30650 1.30959 1.26109 1.24871 1.17131 1.12693 1.10939 1.03137 0.97895 0.95108 0.87637 0.82611 0.74117 0.62600 0.51311
 1.21465 1.22910 1.28483 0.00000 1.28792 1.24664 1.17131 1.12177 1.10423 1.02549 0.97430 0.94881 0.89061 0.00000 0.72951 0.61352 0.50753
 1.21981 1.21672 1.23736 1.26935 1.26522 0.00000 1.18782 1.14138 0.00000 1.04437 0.98834 0.00000 0.87729 0.79546 0.69474 0.60062 0.50144
 1.23013 1.21465 1.20640 1.20536 1.19814 1.20020 1.13828 1.09804 1.07533 1.00268 0.94860 0.91135 0.82900 0.75180 0.67296 0.58927 0.49587
 1.25799 1.22600 1.20227 1.18576 1.16924 1.15067 1.11352 1.07327 1.03612 0.98039 0.92704 0.87368 0.80660 0.73498 0.66357 0.58638 0.49515


Assembly:[1,3] B-10
 1.04437 1.04128 1.04231 1.04231 1.03509 1.02487 1.01372 0.99866 0.97833
 1.13932 1.11868 1.11868 1.13416 1.10939 1.08565 1.05985 1.03199 0.99814
 0.00000 1.19195 1.19092 0.00000 1.19092 1.16305 1.11042 1.06192 1.01620
 1.22600 1.19711 1.19814 1.23013 1.22704 0.00000 1.16408 1.08978 1.03189
 1.23942 1.21156 1.21156 1.23839 1.22188 1.22600 1.19195 1.11145 1.04747
 0.00000 1.24768 1.24768 0.00000 1.24252 1.22704 0.00000 1.14241 1.05985
 1.25490 1.22807 1.22497 1.24664 1.21362 1.19814 1.19504 1.12796 1.06192
 1.25593 1.22910 1.22807 1.24768 1.21259 1.19814 1.19504 1.13003 1.06604
 0.00000 1.25799 1.25284 0.00000 1.23942 1.22291 0.00000 1.15067 1.07120


Assembly:[2,3] A-10
 1.28586 1.22807 1.19195 1.16718 1.15376 1.13622 1.10010 1.06501 1.02477 0.97017 0.91795 0.86150 0.79226 0.72105 0.65191 0.57791 0.48916
 1.28895 1.21672 1.17028 1.14035 1.13932 1.15480 1.10526 1.06708 1.04541 0.97327 0.91754 0.87533 0.78462 0.69948 0.63220 0.56398 0.48080
 1.29927 1.21362 1.14138 1.07636 1.13828 0.00000 1.12900 1.08668 0.00000 0.99092 0.93591 0.00000 0.77967 0.65820 0.60970 0.55480 0.47616
 1.31372 1.21878 1.11352 0.00000 1.06708 1.13416 1.07946 1.03302 1.00309 0.94004 0.89566 0.85686 0.73405 0.00000 0.58658 0.55139 0.47575
 1.33539 1.26006 1.21259 1.10423 1.11558 1.13416 1.06088 0.97771 0.89711 0.88411 0.87286 0.85139 0.75841 0.66563 0.63963 0.56945 0.48049
 1.35603 1.31475 0.00000 1.20949 1.17131 0.00000 1.06398 0.93034 0.00000 0.83612 0.87296 0.00000 0.78957 0.72497 0.00000 0.59566 0.48731
 1.35913 1.29927 1.28173 1.19401 1.13209 1.10113 1.02714 0.95036 0.87172 0.85903 0.84190 0.81950 0.75810 0.71238 0.67606 0.58627 0.48823
 1.36326 1.30443 1.28483 1.18369 1.08772 0.99917 0.98503 0.97213 0.95087 0.88297 0.81290 0.74283 0.72425 0.70433 0.67544 0.58823 0.48875
 1.37048 1.33643 0.00000 1.20330 1.04850 0.00000 0.94479 0.99164 0.00000 0.90732 0.78555 0.00000 0.69154 0.71207 0.00000 0.60227 0.49123


Radial Pin Uncertainties
------------------------
Assembly:[1,1] B-8
 0.000%  0.110%  0.120%  0.000%  0.110%  0.110%  0.000%  0.120%  0.120%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%
 0.000%  0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.080%  0.090%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.000%  0.080%  0.090%  0.090%
 0.000%  0.080%  0.080%  0.000%  0.080%  0.080%  0.080%  0.090%  0.090%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%
 0.120%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.090%  0.090%
```

```
Assembly:[2,1] A-8
 0.110%  0.110%  0.000%  0.120%  0.130%  0.000%  0.130%  0.130%  0.000%  0.130%  0.150%  0.000%  0.150%  0.150%  0.000%  0.170%  0.180%
 0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.110%  0.110%  0.110%  0.120%  0.120%  0.120%
 0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.100%  0.100%  0.110%  0.110%  0.120%  0.120%  0.130%
 0.080%  0.080%  0.000%  0.090%  0.080%  0.000%  0.090%  0.090%  0.000%  0.100%  0.100%  0.000%  0.100%  0.110%  0.000%  0.120%  0.130%
 0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.100%  0.100%  0.100%  0.110%  0.120%  0.120%  0.130%
 0.080%  0.080%  0.080%  0.000%  0.090%  0.090%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.100%  0.000%  0.110%  0.120%  0.130%
 0.080%  0.080%  0.080%  0.080%  0.090%  0.000%  0.090%  0.090%  0.000%  0.090%  0.100%  0.000%  0.110%  0.110%  0.110%  0.120%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.110%  0.110%  0.110%  0.120%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.100%  0.110%  0.110%  0.110%  0.120%

Assembly:[1,2] B-9
 0.110%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%
 0.120%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%
 0.000%  0.080%  0.090%  0.000%  0.090%  0.090%  0.080%  0.080%  0.080%
 0.120%  0.090%  0.090%  0.090%  0.090%  0.000%  0.090%  0.080%  0.080%
 0.130%  0.080%  0.090%  0.090%  0.090%  0.090%  0.090%  0.080%  0.080%
 0.000%  0.090%  0.090%  0.000%  0.090%  0.090%  0.000%  0.090%  0.080%
 0.120%  0.080%  0.090%  0.090%  0.090%  0.090%  0.090%  0.090%  0.080%
 0.120%  0.080%  0.090%  0.080%  0.090%  0.090%  0.090%  0.080%  0.080%
 0.000%  0.080%  0.090%  0.000%  0.090%  0.090%  0.000%  0.080%  0.080%
 0.120%  0.080%  0.090%  0.090%  0.090%  0.080%  0.090%  0.080%  0.080%
 0.120%  0.090%  0.090%  0.090%  0.090%  0.090%  0.090%  0.080%  0.080%
 0.000%  0.090%  0.090%  0.000%  0.090%  0.090%  0.000%  0.090%  0.080%
 0.120%  0.090%  0.090%  0.090%  0.090%  0.090%  0.090%  0.080%  0.080%
 0.120%  0.080%  0.090%  0.090%  0.090%  0.000%  0.090%  0.080%  0.080%
 0.000%  0.090%  0.080%  0.000%  0.090%  0.090%  0.080%  0.080%  0.080%
 0.120%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%

Assembly:[2,2] A-9
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.100%  0.110%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.100%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.090%  0.090%  0.000%  0.100%  0.100%  0.110%  0.120%  0.120%
 0.080%  0.080%  0.080%  0.000%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.090%  0.090%  0.000%  0.100%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.100%  0.100%  0.100%  0.110%  0.120%
 0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.090%  0.090%  0.000%  0.090%  0.100%  0.000%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.100%  0.110%  0.110%  0.120%
 0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.090%  0.090%  0.000%  0.090%  0.100%  0.000%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.100%  0.100%  0.100%  0.110%  0.120%
 0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.090%  0.090%  0.000%  0.090%  0.100%  0.000%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.000%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.000%  0.100%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.090%  0.090%  0.000%  0.090%  0.100%  0.100%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.100%  0.100%  0.110%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.080%  0.090%  0.090%  0.090%  0.100%  0.100%  0.110%  0.110%  0.120%
```

```
Assembly:[1,3] B-10
 0.120%  0.080%  0.090%  0.080%  0.090%  0.080%  0.090%  0.090%  0.090%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%
 0.000%  0.080%  0.080%  0.000%  0.080%  0.080%  0.080%  0.080%  0.090%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.000%  0.080%  0.080%  0.090%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%
 0.000%  0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.080%  0.080%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%
 0.110%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%
 0.000%  0.110%  0.110%  0.000%  0.110%  0.110%  0.000%  0.110%  0.120%

Assembly:[2,3] A-10
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.100%  0.100%  0.110%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.110%  0.110%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.000%  0.080%  0.080%  0.000%  0.090%  0.090%  0.000%  0.100%  0.110%  0.110%  0.120%  0.120%
 0.080%  0.080%  0.080%  0.000%  0.080%  0.080%  0.090%  0.080%  0.080%  0.090%  0.090%  0.090%  0.100%  0.000%  0.110%  0.120%  0.120%
 0.070%  0.080%  0.080%  0.090%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.110%  0.110%  0.110%  0.120%
 0.070%  0.080%  0.000%  0.080%  0.080%  0.000%  0.080%  0.090%  0.000%  0.100%  0.090%  0.000%  0.100%  0.100%  0.000%  0.110%  0.120%
 0.070%  0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.100%  0.100%  0.100%  0.120%  0.120%
 0.080%  0.080%  0.080%  0.080%  0.080%  0.090%  0.090%  0.090%  0.090%  0.090%  0.100%  0.100%  0.100%  0.100%  0.110%  0.110%  0.120%
 0.110%  0.110%  0.000%  0.110%  0.120%  0.000%  0.130%  0.120%  0.000%  0.130%  0.140%  0.000%  0.150%  0.140%  0.000%  0.160%  0.170%
```

APPENDIX J – PROBLEM 5-2D DATA AND RESULTS

The following are the isotopics and results for Problem 5-2D, in ASCII form. No pin powers are provided due to the sheer size of the dataset. All data is based on ENDF/B-VII.0.

```
mixture = fuel (2.11%)
  8016  4.57591E-02
 92234  4.04814E-06
 92235  4.88801E-04
 92236  2.23756E-06
 92238  2.23844E-02

mixture = fuel (2.619%)
  8016  4.57617E-02
 92234  5.09503E-06
 92235  6.06709E-04
 92236  2.76809E-06
 92238  2.22663E-02

mixture = fuel (3.10%)
  8016  4.57642E-02
 92234  6.11864E-06
 92235  7.18132E-04
 92236  3.29861E-06
 92238  2.21546E-02

mixture = gap
  2004  2.68714E-05

mixture =  cladding
(Zircaloy-4)
 24050  3.30121E-06
 24052  6.36606E-05
 24053  7.21860E-06
 24054  1.79686E-06
 26054  8.68307E-06
 26056  1.36306E-04
 26057  3.14789E-06
 26058  4.18926E-07
 40090  2.18865E-02
 40091  4.77292E-03
 40092  7.29551E-03
 40094  7.39335E-03
 40096  1.19110E-03
 50112  4.68066E-06
 50114  3.18478E-06
 50115  1.64064E-06
 50116  7.01616E-05
 50117  3.70592E-05
 50118  1.16872E-04
 50119  4.14504E-05
 50120  1.57212E-04
 50122  2.23417E-05
 50124  2.79392E-05
 72174  3.54138E-09
 72176  1.16423E-07
 72177  4.11686E-07
 72178  6.03806E-07
 72179  3.01460E-07
 72180  7.76449E-07
```

```
mixture = moderator
  1001  4.96224E-02
  5010  1.07070E-05
  5011  4.30971E-05
  8016  2.48112E-02

mixture = pyrex
  5010  9.63266E-04
  5011  3.90172E-03
  8016  4.67761E-02
 14028  1.81980E-02
 14029  9.24474E-04
 14030  6.10133E-04

mixture = stainless steel
  6000  3.20895E-04
 14028  1.58197E-03
 14029  8.03653E-05
 14030  5.30394E-05
 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

mixture = carbon steel
  6000  3.93598E-03
 26054  4.89841E-03
 26056  7.68945E-02
 26057  1.77583E-03
 26058  2.36330E-04
```

```
mixture = AIC
 47107  2.36159E-02
 47109  2.19403E-02
 48106  3.41523E-05
 48108  2.43165E-05
 48110  3.41250E-04
 48111  3.49720E-04
 48112  6.59276E-04
 48113  3.33873E-04
 48114  7.84957E-04
 48116  2.04641E-04
 49113  3.44262E-04
 49115  7.68050E-03

mixture = B4C
  5010  1.52689E-02
  5011  6.14591E-02
  6000  1.91820E-02
```

Problem 5-2D ENDF/B-VII.0 Eigenvalue Results

Case	k-eff	Sigma
5A-2D	1.004085	0.000008
5B-2D	0.991496	0.000008
5C-2D	0.990227	0.000009

Problem 5-2D ENDF/B-VII.0 Assembly Power Results

```
5A-2D Assembly Powers                                    5A-2D Assembly Power Uncertainties
----------------------                                   ----------------------------------
  1.00552                                                  0.008%
  0.93066  0.99949                                         0.005%  0.004%
  1.01697  0.90481  1.05689                                0.005%  0.004%  0.004%
  0.99606  1.08288  1.03660  1.16462                       0.005%  0.004%  0.004%  0.003%
  1.12476  1.05540  1.17037  1.09891  1.31539             0.005%  0.004%  0.003%  0.003%  0.003%
  1.05194  1.15555  1.14177  1.15183  0.91318  0.92427    0.005%  0.003%  0.003%  0.003%  0.004%  0.004%
  1.06684  1.04799  1.08590  1.03952  0.94474  0.63213    0.005%  0.004%  0.004%  0.004%  0.004%  0.005%
  0.77672  0.88808  0.78874  0.64863                       0.006%  0.004%  0.004%  0.005%

5B-2D Assembly Powers                                    5B-2D Assembly Power Uncertainties
----------------------                                   ----------------------------------
  0.44842                                                  0.011%
  0.74892  0.88530                                         0.006%  0.004%
  0.93490  0.85852  1.04181                                0.005%  0.004%  0.004%
  0.82972  0.99760  1.01457  1.07808                       0.006%  0.004%  0.004%  0.004%
  0.56050  0.94245  1.16498  0.94907  0.62417             0.007%  0.004%  0.003%  0.004%  0.005%
  1.02557  1.21707  1.24003  1.14941  0.78718  0.85283    0.005%  0.003%  0.003%  0.003%  0.004%  0.004%
  1.28281  1.26577  1.30174  1.18218  0.99216  0.63882    0.005%  0.003%  0.003%  0.003%  0.004%  0.005%
  1.00018  1.14360  0.99841  0.79299                       0.005%  0.003%  0.004%  0.004%

5C-2D Assembly Powers                                    5C-2D Assembly Power Uncertainties
----------------------                                   ----------------------------------
  0.39871                                                  0.012%
  0.72472  0.86744                                         0.006%  0.004%
  0.92003  0.84835  1.03468                                0.005%  0.004%  0.004%
  0.80588  0.98327  1.00774  1.06447                       0.006%  0.004%  0.004%  0.004%
  0.50675  0.92670  1.16164  0.92946  0.55892             0.007%  0.004%  0.003%  0.004%  0.005%
  1.02219  1.22435  1.25138  1.14927  0.77270  0.84533    0.005%  0.003%  0.003%  0.003%  0.004%  0.004%
  1.31060  1.29339  1.32912  1.20029  0.99890  0.64007    0.005%  0.003%  0.003%  0.003%  0.004%  0.005%
  1.02931  1.17655  1.02537  0.81145                       0.005%  0.003%  0.004%  0.004%
```

Radial Reflector Sensitivity Study

A sensitivity analysis of the radial reflector model was performed taking advantage of the KENO-VI general geometry modeling capabilities. In particular, various potential structural models were constructed and the executed with KENO-VI to assess their impacts on the eigenvalue and pin power distribution. These simulations are described below and shown in Figure J-1. The power distributions from these models are available by request. In particular, the baffle-only model may serve as an appropriate reference for some methods that do not support the cylindrical objects.

The following cases for modeling the radial core structure for the 2D WBN1 core are considered. Many neutronics methods may be limited in flexibility to model the specific geometry, including baffle, barrel, neutron pads, and vessel. However, since the effects of these items are minor, in most cases a simple radial approximation is sufficient, especially for low leakage core designs.

Case 1: Full reflector model; the core barrel, neutron pads, and vessel are all included explicitly as described in Section 1.13. A vacuum boundary is placed outside the cylindrical vessel.

Case 2: A baffle-only model; a 2.85 cm thick solid stainless steel baffle is the only structural material outside of the fuel. A jagged layer of moderator is applied outside of the core with thickness equal to one assembly pitch. Void is used outside of this jagged moderator layer, and a vacuum condition is used at the square boundary. This model is consistent with the VERA neutronics codes' capabilities at the time of this revision.

Case 3: A full reflector model but without the neutron pad. Because the pad is not a full cylinder, most methods will lack the ability to model it. This case provides the worth of ignoring it completely.

Case 4: A full reflector model smearing the volume of the neutron pad with the cylindrical core barrel. This results in a significant reduction in the effective pad thickness at the location nearest to fuel.

Case 5: A full reflector model using a full cylindrical pad of equivalent thickness. This results in a significant increase in the volume of pad material, but nearly conserves the steel mass local to the nearest corner peripheral fuel assemblies.

Each of these models was executed with CE KENO-VI using quarter symmetry and input parameters and particle numbers consistent with Problem 5A-2D (uncontrolled). The effects of the various reflector components are summarized in Table J-1 by comparison of each case with the reference geometry (Case 1). These include the effect on the 2D core eigenvalue and assembly and pin power distributions (normalized fission rates). The power distribution comparisons are provided in Figures J-2 to J-5.
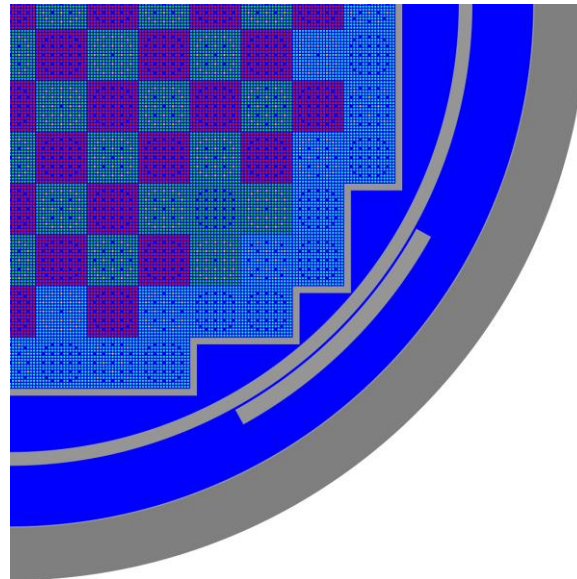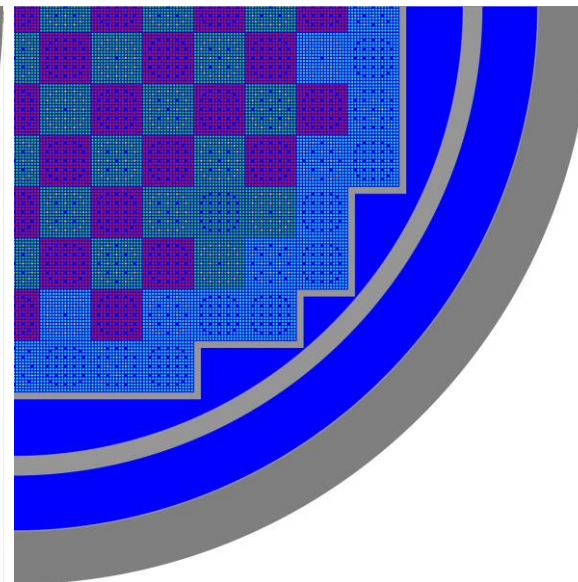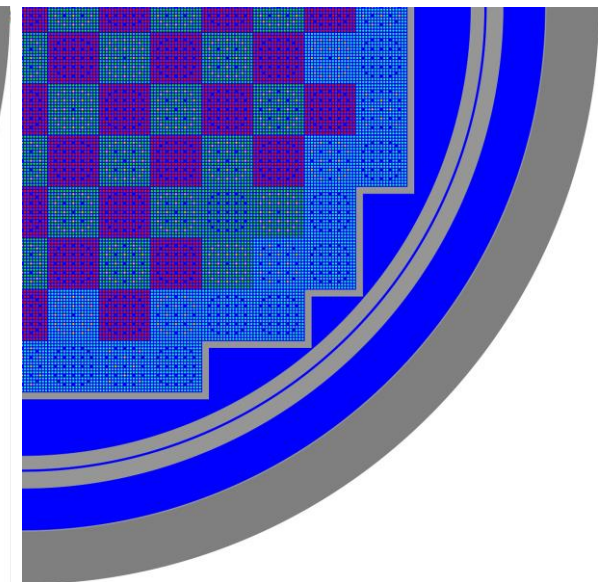
Case 1: Full Actual Reflector
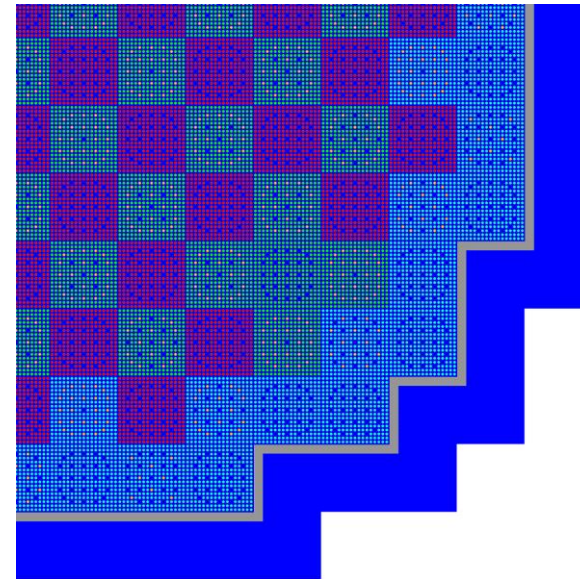
Case 2: Baffle Only
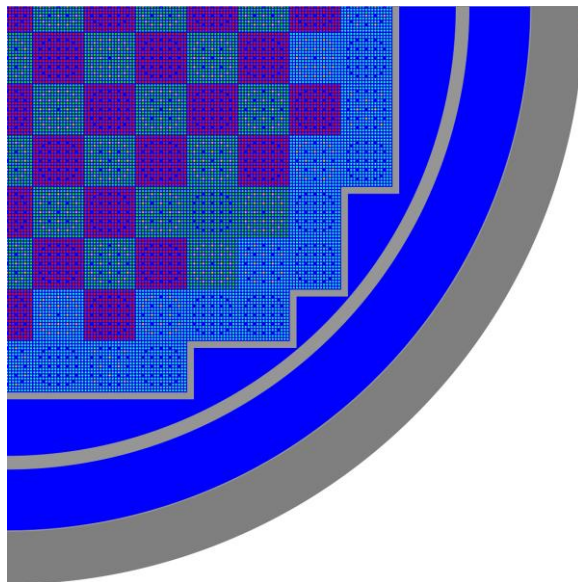
Case 3: No Neutron Pad

Case 4: Pad Smeared into Barrel

Case 5: Full Cylinder Pad

Figure J-1: KENO-VI 2D Core Radial Reflector Models

**Table J-1: Comparison of Radial Reflector Models for the 2D Core**

Parameter (Compared to Case 1)	Case 2	Case 3	Case 4	Case 5
Eigenvalue Difference (pcm)	-4.5 ± 1.1	-2.6 ± 1.1	-1.1 ± 1.1	-1.1 ± 1.1
Maximum Assembly Power Difference (absolute difference)	-0.57% ± 0.01%	0.09% ± 0.01%	0.08% ± 0.01%	0.11% ± 0.01%
Pin Power RMS Difference (absolute differences)	0.19% ± 0.08%	0.09% ± 0.08%	0.09% ± 0.08%	0.09% ± 0.08%
Maximum Pin Power Difference (absolute difference)	1.01% ± 0.17%	0.41% ± 0.12%	0.41% ± 0.12%	0.43% ± 0.11%
Maximum Pin Power Difference (relative error, for Powers >= 0.8)	-0.81% ± 0.09%	-0.41% ± 0.12%	0.44% ± 0.12%	-0.36% ± 0.11%
Maximum Pin Power Difference (relative error, for Powers < 0.8)	-5.07% ± 0.19%	-1.50% ± 0.19%	-0.49% ± 0.12%	0.47% ± 0.17%

These results, in conjunction with the power distribution figures below, support the following conclusions:

1. Exclusion of the core barrel, neutron pad, and vessel results in a observable yet small difference in assembly (0.5%) and pin (1.0 %) powers and reactivity (<5 pcm).

2. Complete exclusion of the neutron pad results in very small differences in assembly and pin powers which are almost within the uncertainty of the calculation, except for relative power errors in the few rods closest to the pad (1.5%) for pins with powers less than 0.5.

3. Within the statistical uncertainty of the comparisons, it appears equivalent to model the neutron pad explicitly or by one of the other methods shown above (smeared into barrel or thickness preserved). However, based on the power distribution comparisons shown below, Case 4 is the closet match.
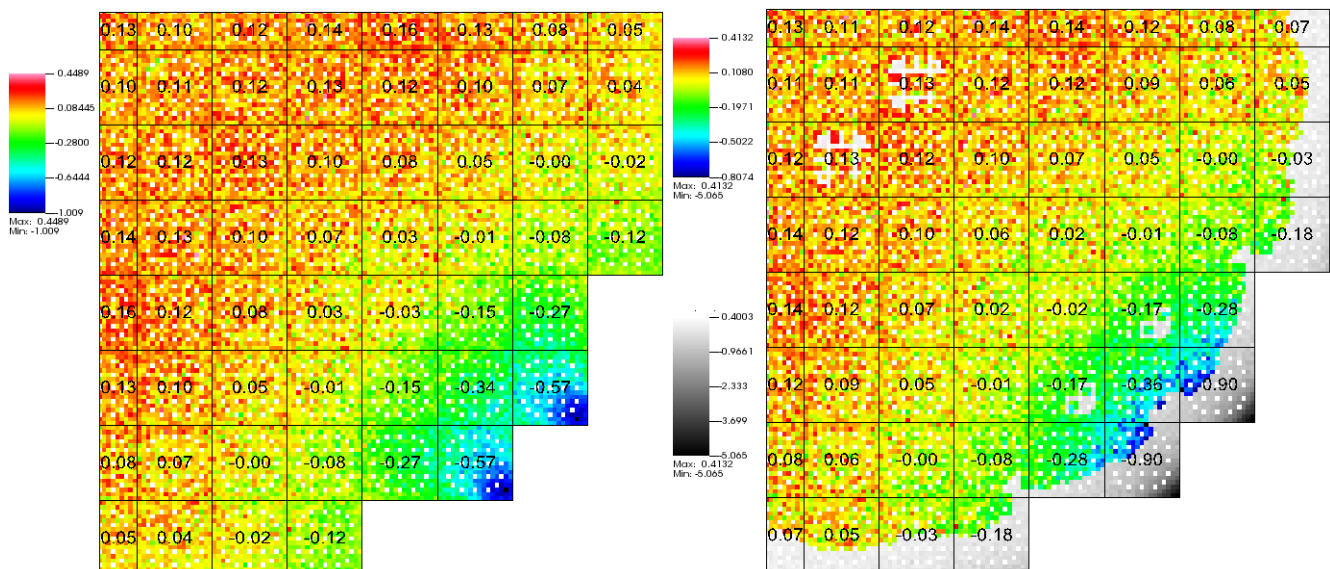
Figure J-2: KENO-VI Absolute and Relative Pin Power Comparison - Case 1 vs Case 2 (%)
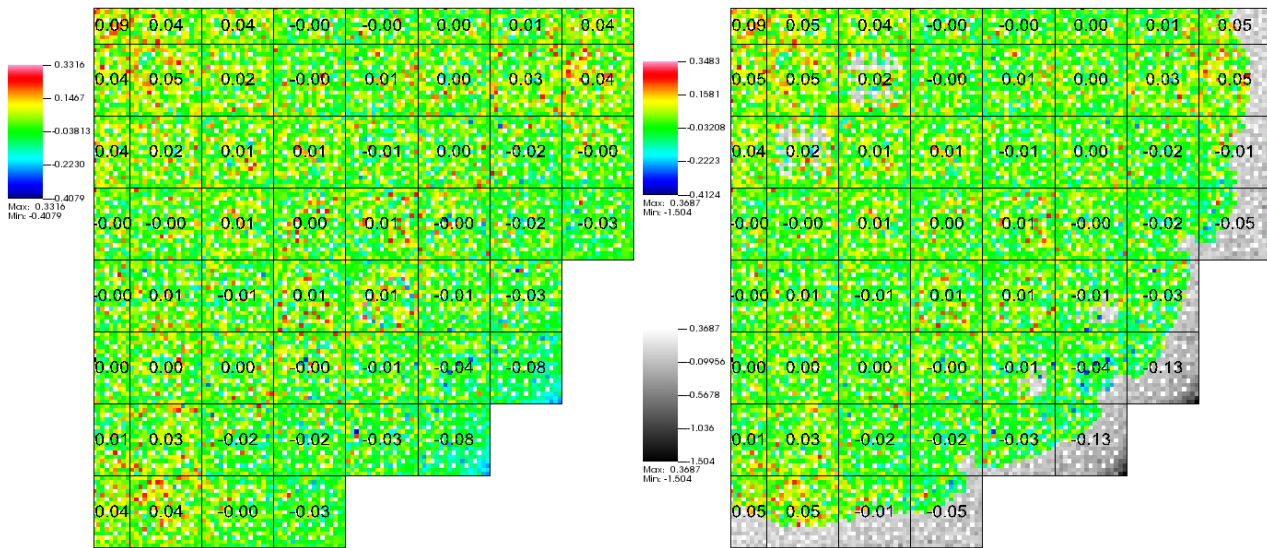
Figure J-3: KENO-VI Absolute and Relative Pin Power Comparison - Case 1 vs Case 3 (%)
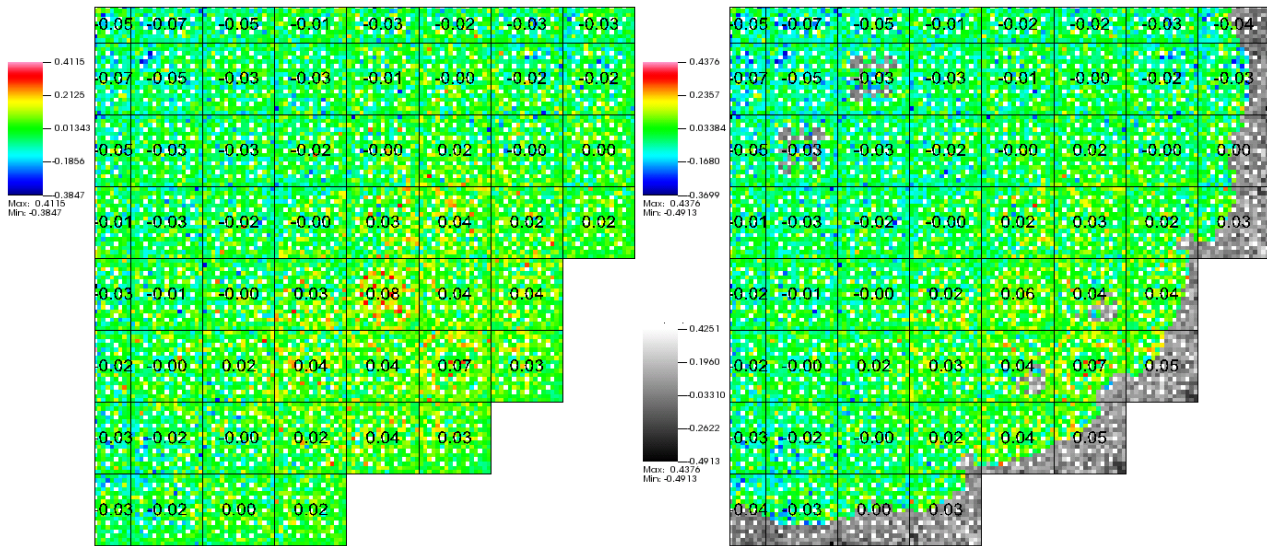

Figure J-4: KENO-VI Absolute and Relative Pin Power Comparison - Case 1 vs Case 4 (%)
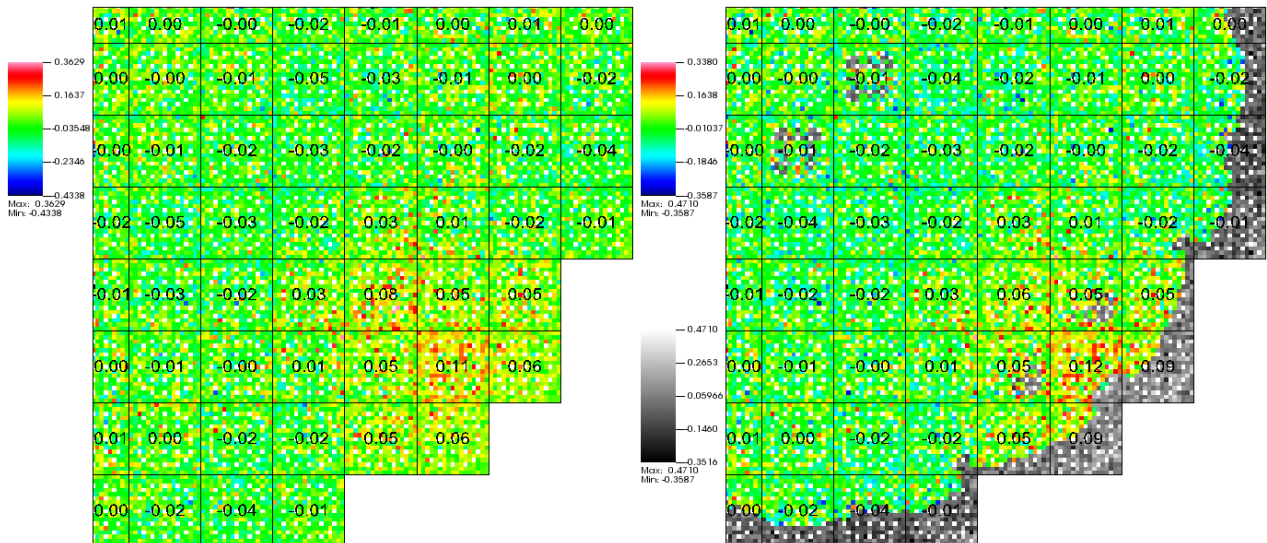

Figure J-5: KENO-VI Absolute and Relative Pin Power Comparison - Case 1 vs Case 5 (%)

APPENDIX K – PROBLEM 10 SHUFFLE DATA

Provided below are the WBN1C2 shuffle, IFBA, and WABA maps, respectively. 128L represents 128 IFBA with 132" length.

```
R    P    N    M    L    K    J    H    G    F    E    D    C    B    A
                    N-6  K-7  D-3  E-6  M-3  F-7  C-6                       1
               F-14 D-2  FEED FEED FEED A-11 FEED FEED FEED M-2  K-14       2
          B-10 FEED FEED FEED G-2  FEED H-13 FEED J-2  FEED FEED FEED P-10  3
          P-12 FEED R-10 B-13 FEED L-2  FEED E-2  FEED P-13 K-1  FEED B-12  4
     K-3  FEED FEED C-14 FEED G-4  FEED H-15 FEED J-4  FEED N-14 FEED FEED F-3  5
     J-6  FEED P-9  FEED M-9  L-1  J-1  FEED G-1  A-5  D-9  FEED B-9  FEED G-6  6
     N-12 FEED FEED P-5  FEED R-7  FEED C-13 FEED A-7  FEED B-5  FEED FEED C-12 7
     K-5  E-1  C-8  FEED A-8  FEED C-3  H-14 N-13 FEED R-8  FEED N-8  L-15 F-11 8
     N-4  FEED FEED P-11 FEED R-9  FEED N-3  FEED A-9  FEED B-11 FEED FEED C-4  9
     J-10 FEED P-7  FEED M-7  R-11 J-15 FEED G-15 E-15 D-7  FEED B-7  FEED G-10 10
     K-13 FEED FEED C-2  FEED G-12 FEED H-1  FEED J-12 FEED N-2  FEED FEED F-13 11
          P-4  FEED F-15 B-3  FEED L-14 FEED E-14 FEED P-3  A-6  FEED B-4       12
          B-6  FEED FEED FEED G-14 FEED H-3  FEED J-14 FEED FEED FEED P-6       13
               F-2  D-14 FEED FEED FEED R-5  FEED FEED FEED M-14 K-2           14
                    N-10 K-9  D-13 L-10 M-13 F-9  C-10                         15


R    P    N    M    L    K    J    H    G    F    E    D    C    B    A
                    ---- ---- ---- ---- ---- ---- ----                     1
               ---- ---- 48I  48I  48I  ---- 48I  48I  48I  ---- ----       2
          ---- ---- 104I 128I ---- 128L ---- 128L ---- 128I 104I ---- ----  3
          ---- 104I ---- ---- 104I ---- 128I ---- 104I ---- ---- 104I ----   4
     ---- 48I  128I ---- 128L ---- 104I ---- 104I ---- 128L ---- 128I 48I  ---- 5
     ---- 48I  ---- 104I ---- ---- ---- 128L ---- ---- ---- 104I ---- 48I  ---- 6
     ---- 48I  128L ---- 104I ---- 104I ---- 104I ---- 104I ---- 128L 48I  ---- 7
     ---- ---- ---- 128I ---- 128L ---- ---- ---- 128L ---- 128I ---- ---- ---- 8
     ---- 48I  128L ---- 104I ---- 104I ---- 104I ---- 104I ---- 128L 48I  ---- 9
     ---- 48I  ---- 104I ---- ---- ---- 128L ---- ---- ---- 104I ---- 48I  ---- 10
     ---- 48I  128I ---- 128L ---- 104I ---- 104I ---- 128L ---- 128I 48I  ---- 11
          ---- 104I ---- ---- 104I ---- 128I ---- 104I ---- ---- 104I ----      12
          ---- ---- 104I 128I ---- 128L ---- 128L ---- 128I 104I ---- ----      13
               ---- ---- 48I  48I  48I  ---- 48I  48I  48I  ---- ----          14
                    ---- ---- ---- ---- ---- ---- ----                         15


R    P    N    M    L    K    J    H    G    F    E    D    C    B    A
                    ---- ---- ---- ---- ---- ---- ----                     1
               ---- 4    ---- ---- ---- ---- ---- ---- ---- 4    ----       2
          ---- 4    ---- ---- 8    ---- ---- ---- 8    ---- ---- 4    ----  3
          ---- ---- ---- ---- ---- 8    ---- 8    ---- ---- ---- ---- ----  4
     ---- ---- ---- 8    ---- ---- ---- ---- ---- ---- ---- 8    ---- ---- ---- 5
     ---- ---- ---- ---- 8    ---- ---- ---- ---- ---- 8    ---- ---- ---- ---- 6
     ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- 7
     ---- ---- ---- ---- 8    ---- ---- ---- ---- ---- 8    ---- ---- ---- ---- 8
     ---- ---- ---- 8    ---- ---- ---- ---- ---- ---- ---- 8    ---- ---- ---- 9
     ---- ---- ---- ---- ---- ---- 8    ---- 8    ---- ---- ---- ---- ---- ---- 10
          ---- 4    ---- ---- 8    ---- ---- ---- 8    ---- ---- 4    ----      11
          ---- ---- 4    ---- ---- ---- ---- ---- ---- ---- 4    ---- ----      12
               ---- ---- ---- ---- ---- ---- ---- ---- ---- ---- ----          13
                    ---- ---- ---- ---- ---- ---- ----                         14
                                                                               15
```