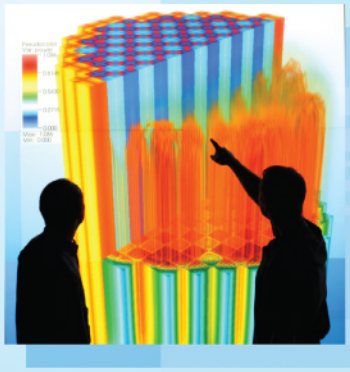
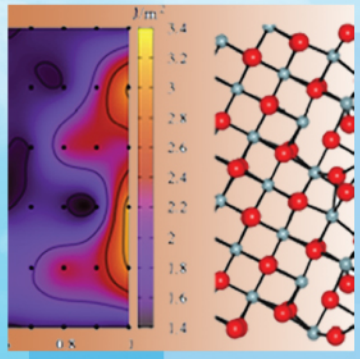
A. Godfrey, VERA Core Physics Benchmark Progression Problem Specifications, CASL Technical Report: CASL-U-2012-0131-002

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 2

March 29, 2013

Andrew T. Godfrey
Advanced Modeling Applications
Oak Ridge National Laboratory

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

# 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. |
| | | | |

**Document pages that are:**

Export Controlled __None_____

IP/Proprietary/NDA Controlled__None_____

Sensitive Controlled__None_____

**Requested Distribution:**

To: N/A

Copy: N/A

# EXECUTIVE SUMMARY

Provided are the detailed specifications for the AMA Core Physics Benchmark Progression Problems 1 through 5. These problems were selected to assist 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 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 transport solution.

Problems 1 to 5 represent geometries that are contained in the WBN1 initial startup core. Problem 5 provides specification for reference models and results that are directly comparable 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.

# CONTENTS

REVISION LOG ..... ii

EXECUTIVE SUMMARY ..... iii

CONTENTS ..... v

FIGURES ..... vi

TABLES ..... ix

ACRONYMS ..... xii

INTRODUCTION ..... 1

1. GEOMETRY ..... 3

2. MATERIALS ..... 17

3. OPERATING CONDITIONS ..... 17

4. CORE PHYSICS PROBLEMS ..... 18
Problem #1: 2D HZP BOC Pin Cell ..... 18
Problem #2: 2D HZP BOC Fuel Lattice ..... 22
Problem #3: 3D HZP Assembly ..... 38
Problem #4: 3D HZP 3x3 Assembly Control Rod Worth ..... 45
Problem #5: Physical Reactor Zero Power Physics Tests ..... 54

5. MISCELLANEOUS BENCHMARKS ..... 64
Problem #4-2D: 2D HZP BOC 3x3 Assembly (Colorset) ..... 64
Problem #REF1-2D: 2D HZP BOC Reflector – Case 1 ..... 71
Problem #5-2D: 2D HZP BOC Quarter Core ..... 78

REFERENCES ..... 87

APPENDIX A – PROBLEM 1 DATA AND RESULTS ..... 88

APPENDIX B – PROBLEM 2 ENDF/B-VII DATA AND RESULTS ..... 91

APPENDIX C – PROBLEM 2 ENDF/B-VI DATA AND RESULTS ..... 100

APPENDIX D – PROBLEM 4-2D DATA AND RESULTS ..... 110

APPENDIX E – PROBLEM REF1-2D DATA AND RESULTS ..... 122

APPENDIX F – PROBLEM 5-2D DATA AND RESULTS ..... 127

# FIGURES

Figure 1: Ten AMA Core Physics Benchmark Progression Problems ..... 2

Figure 2. Fuel Rod Arrangement ..... iii

Figure 3: 17x17 Lattice Fuel Rod and Thimble Arrangement ..... 4

Figure 4. Axial Fuel Assembly Arrangement ..... 6

Figure 5. Pyrex Configurations (Octant Symmetry) ..... 8

Figure 6. RCCA Assembly ..... 9

Figure 7. IFBA Configurations (Octant Symmetry) ..... 11

Figure 8. Gadolinia Configurations (Octant Symmetry) ..... 13

Figure 9. Core Fuel and Poison Loading Pattern (in quarter symmetry) ..... 14

Figure 10. Core RCCA Bank Positions (in quarter symmetry) ..... 15

Figure 11. Core Incore Instrumentation Locations ..... 15

Figure 12. Radial Core Structure ..... 16

Figure P1-1: Problem 1 KENO-VI Geometry ..... 18

Figure P2-1: Problem 2 KENO-VI Geometry ..... 22

Figure P2-2: Problem 2 Lattice Layouts (Octant Symmetry) ..... 24

Figure P2-3: Problem 2A (565K) CE KENO-VI Power Distribution Results ..... 29

Figure P2-4: Problem 2B (600K) CE KENO-VI Power Distribution Results ..... 29

Figure P2-5: Problem 2C (900K) CE KENO-VI Power Distribution Results ..... 30

Figure P2-6: Problem 2D (1200K) CE KENO-VI Power Distribution Results ..... 30

Figure P2-7: Problem 2E (12 Pyrex) CE KENO-VI Power Distribution Results ..... 31

Figure P2-8: Problem 2F (24 Pyrex) CE KENO-VI Power Distribution Results ..... 31

Figure P2-9: Problem 2G (AIC) CE KENO-VI Power Distribution Results ..... 32

Figure P2-10: Problem 2H ($B_4C$) CE KENO-VI Power Distribution Results ..... 32

Figure P2-11: Problem 2I (Instrument Thimble) CE KENO-VI Power Distribution Results ..... 33

Figure P2-12: Problem 2J (Instrument and Pyrex) CE KENO-VI Power Distribution Results.....33

Figure P2-13: Problem 2K (Zoned and 24 Pyrex) CE KENO-VI Power Distribution Results .....34

Figure P2-14: Problem 2L (80 IFBA) CE KENO-VI Power Distribution Results .....34

Figure P2-15: Problem 2M (128 IFBA) CE KENO-VI Power Distribution Results .....35

Figure P2-16: Problem 2N (104 IFBA + 20 WABA) CE KENO-VI Power Distribution Results ....35

Figure P2-17: Problem 2O (12 Gadolinia) CE KENO-VI Power Distribution Results.....36

Figure P2-18: Problem 2P (24 Gadolinia) CE KENO-VI Power Distribution Results .....36

Figure P2-19: Problem 2Q (Zircaloy Spacer Grid) CE KENO-VI Power Distribution Results .....37

Figure P3-1: Problem 3 Axial Geometry (without end plugs) .....39

Figure P3-2: Problem 3 Reference Model.....42

Figure P4-1: Problem 4 Assembly, Poison, and Control Layout .....45

Figure P4-2: Problem 4 Radial KENO-VI Geometry.....49

Figure P4-3: Problem 4 Axial KENO-VI Geometry (not to proportion).....49

Figure P4-4: Problem 4 Differential Control Rod Worth .....52

Figure P4-5: Problem 4 Integral Control Rod Worth .....53

Figure P5-1: Problem 5 Assembly and Poison Layout in Quarter Symmetry.....54

Figure P5-2: Problem 5 Radial KENO-VI Geometry.....58

Figure P5-3: Problem 5 Axial KENO-VI Geometry (not to proportion).....59

Figure M1-1: Problem 4-2D Assembly, Poison, and Control Layout .....64

Figure M1-2: Problem 4-2D Radial Geometry.....66

Figure M1-3: Problem 4-2D Assembly Power Distributions.....68

Figure M1-4: Problem 4-2D Uncontrolled Pin Power Distribution .....69

Figure M1-5: Problem 4-2D Controlled Pin Power Distribution .....69

Figure M1-6: Problem 4-2D Uncontrolled Pin Power Estimated Uncertainties .....70

Figure M1-7: Problem 4-2D Controlled Pin Power Estimated Uncertainties .....70

Figure M2-1: Problem REF1-2D Assembly and Poison Configuration .....71

Figure M2-2: Problem REF1-2D Radial Geometry....74

Figure M2-3: Problem REF1-2D Assembly Power Distributions....76

Figure M2-4: Problem REF1-2D Pin Power Distribution....77

Figure M2-5: Problem REF1-2D Pin Power Estimated Uncertainties....77

Figure M3-2: Problem 5-2D Radial Geometry....80

Figure M3-3: Problem 5-2D Assembly Power Distributions and Uncertainties....84

Figure M3-4: Problem 5-2D Uncontrolled Pin Power Distribution....85

Figure M3-5: Problem 5-2D Controlled Pin Power Distribution....85

Figure M3-6: Problem 5-2D Uncontrolled Pin Power Estimated Uncertainties....86

Figure M3-7: Problem 5-2D Controlled Pin Power Estimated Uncertainties....86

# TABLES

Table 1: Fuel Rod Specification (Ref. 1) ..... iii

Table 2: 17x17 Lattice Specification (Ref. 1) ..... 4

Table 3: Spacer Grid Specification ..... 5

Table 4: Fuel Assembly Specification (Ref. 1) ..... 6

Table 5: Assembly Nozzle and Core Plate Specification ..... 6

Table 6: Pyrex Rod Specification ..... vii

Table 7: Pyrex Isotopics ..... 8

Table 8: RCCA Rod and Drive Specification ..... ix

Table 9: Thimble Plug Specification ..... 9

Table 10: Instrument Thimble Specification ..... x

Table 11: IFBA Fuel Rod Specification ..... 10

Table 12: IFBA Isotopics ..... 11

Table 13: WABA Rod Specification ..... xii

Table 14: WABA Isotopics ..... 12

Table 15: Gadolinia Fuel Rod Specification ..... 13

Table 16: Core Structure Specification (Ref. 8) ..... 16

Table 17: Example LEU Isotopic Equations ..... 17

Table P1-1: Problem 1 Calculations ..... 18

Table P1-2: Problem 1 Input Specification ..... 18

Table P1-3: Problem 1 Calculated Fuel Isotopic Input ..... 20

Table P1-4: Reference Mixing Table ..... 21

Table P1-5: Problem 1 Reference Solution Results ..... 21

Table P2-1: Problem 2 Calculations ..... 23

Table P2-2: Problem 2 Input Specification ..... 23

Table P2-3: Problem 2 Calculated Fuel Isotopic Input vs. Enrichment ..... 26

Table P2-4: Reference Mixing Table ..... 27

Table P2-5: Problem 2 Reference Solution Eigenvalue Results ..... 28

Table P3-1: Problem 3 Input Specification ..... 38

Table P3-2: Problem 3 Calculated Isotopic Input ..... 40

Table P3-3: Reference Mixing Table ..... 43

Table P3-4: Problem 3 Reference Solution Eigenvalue Results ..... 44

Table P4-1: Problem 4 Input Specification ..... 46

Table P4-2: Problem 4 Calculated Isotopic Input ..... 47

Table P4-3: Reference Mixing Table ..... 50

Table P4-4: Problem 4 Reference Solution Eigenvalue Results ..... 52

Table P5-1: Problem 4 Input Specification ..... 55

Table P5-2: Problem 5 Calculated Fuel Isotopic Input vs. Enrichment ..... 56

Table P5-3: Reference Mixing Table ..... 60

Table P5-4: Problem 5 Reference Solution Eigenvalue Results ..... 62

Table P5-5: Problem 5 Reference Solution ZPPT Results ..... 63

Table M1-1: Problem 4-2D Input Specification ..... 64

Table M1-2: Problem 4-2D Calculated Fuel Isotopic Input vs. Enrichment ..... 65

Table M1-3: Problem 4-2D Maximum Pin Power Uncertainty vs. Pin Power ..... 66

Table M1-4: Reference Mixing Table ..... 67

Table M1-5: Problem 4-2D Reference Solution Results ..... 68

Table M1-6: Problem 4-2D Reference Solution Power Statistics ..... 68

Table M2-1: Problem REF1-2D Input Specification ..... 72

Table M2-2: Problem REF1-2D Calculated Fuel Isotopic Input vs. Enrichment ..... 73

Table M2-3: Problem REF1-2D Maximum Pin Power Uncertainty vs. Pin Power ..... 73

Table M2-4: Reference Mixing Table ..... 75

Table M2-5: Problem REF1-2D Reference Solution Power Statistics ..... 76

Table M3-1: Problem 5-2D Input Specification ..... 78

Table M3-2: Problem 5-2D Calculated Fuel Isotopic Input vs. Enrichment ..... 79

Table M3-3: Problem 5-2D Maximum Pin Power Uncertainty vs. Pin Power ..... 80

Table M3-4: Reference Mixing Table ..... 82

Table M3-5: Problem 5-2D Reference Solution Results ..... 83

Table M3-6: Problem 5-2D Reference Solution Power Statistics ..... 83

# ACRONYMS

| | |
|---|---|
| 2D | Two-Dimensional |
| 3D | Three-Dimensional |
| AIC | Silver-Indium-Cadmium control rods |
| AMA | CASL's Advanced Modeling Applications Focus Area |
| ARI | All Rods In |
| ARO | All Rods Out |
| $B_4C$ | Boron Carbide control rods |
| 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 |
| FP | Full Power |
| Gad | Gadolinia integral burnable absorber ($Gd_2O_3$) |
| 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) |
| PCM | Percent milli ($10^{-5}$) |
| PWR | Pressurized Water Reactor |
| RCCA | Rod Cluster Control Assembly |
| TVA | Tennessee Valley Authority |
| VERA | Virtual Environment for Reactor Applications |
| WABA | Wet Annular Burnable Absorber |
| WBN1 | Watts Bar Nuclear 1 (here Cycle 1) |
| WEC | Westinghouse Electric Company |
| ZPPT | Zero Power Physics Tests |

# INTRODUCTION

The AMA 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 first five problems, ranging from a simple 2D pin cell to a 3D reactor core configuration with control rods and burnable poisons consistent with actual nuclear power plant data. 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 used and these isotopics and results are located in the appendices.

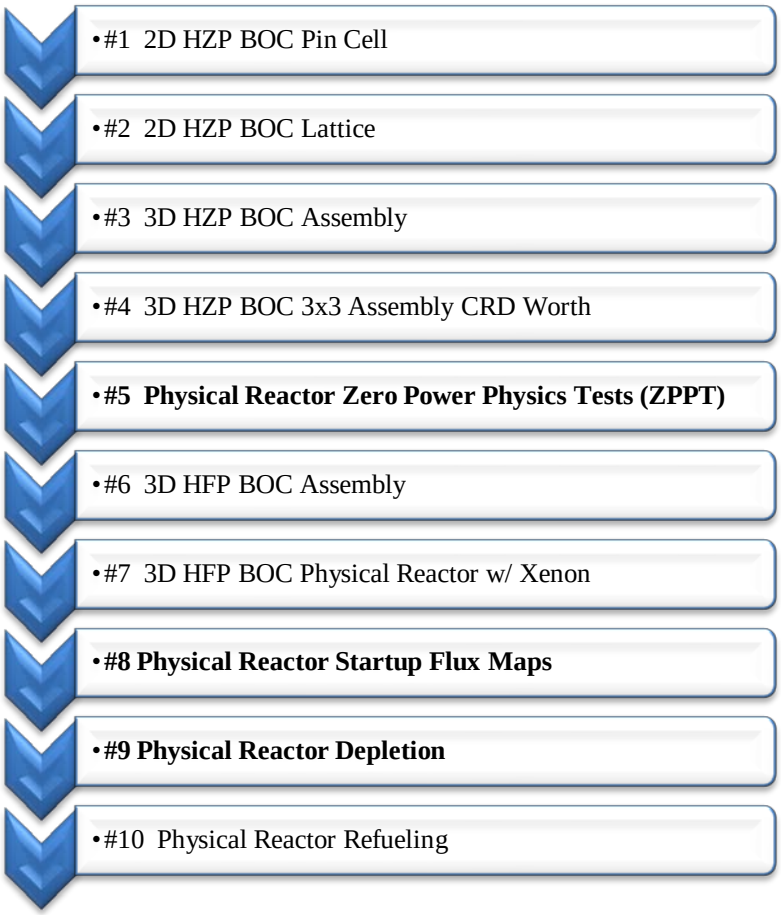
Each problem may be solved to different degrees of satisfaction. The section entitled "Capabilities" provides a list of many required or desired features of an excellent reactor analysis tool that could be demonstrated for each problem. It should be discouraged to approach these problems as "solved" 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.

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(α,β) 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.




* **Bold** indicates comparisons against measured data

**Figure 1: Ten AMA Core Physics Benchmark Progression Problems**

Currently this document contains specifications for the first five problems above. 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".

# 1. GEOMETRY

Each of problems in this specification is based on actual fuel and core geometries used in the Watts Bar Nuclear 1 (WBN1) initial core loading. This fuel is a Westinghouse 17x17 design utilizing discrete Pyrex burnable poisons and hybrid AIC/$B_4C$ 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.

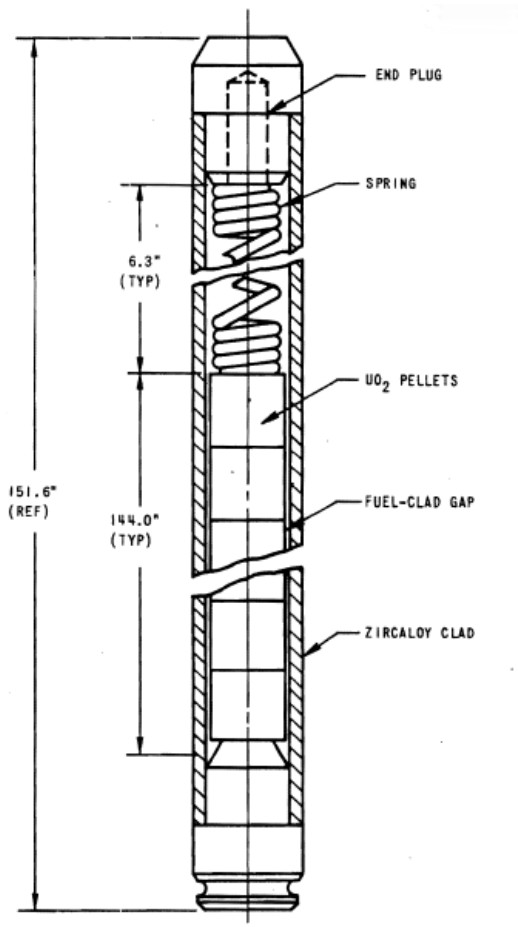



**Figure 2. Fuel Rod Arrangement**
(Ref. 1 Figure 4.2-3, in inches)

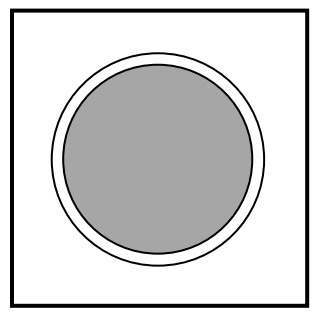


**Table 1: Fuel Rod Specification (Ref. 1)**

| 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 / Caps 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 spring is unknown.

## 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) rods 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.

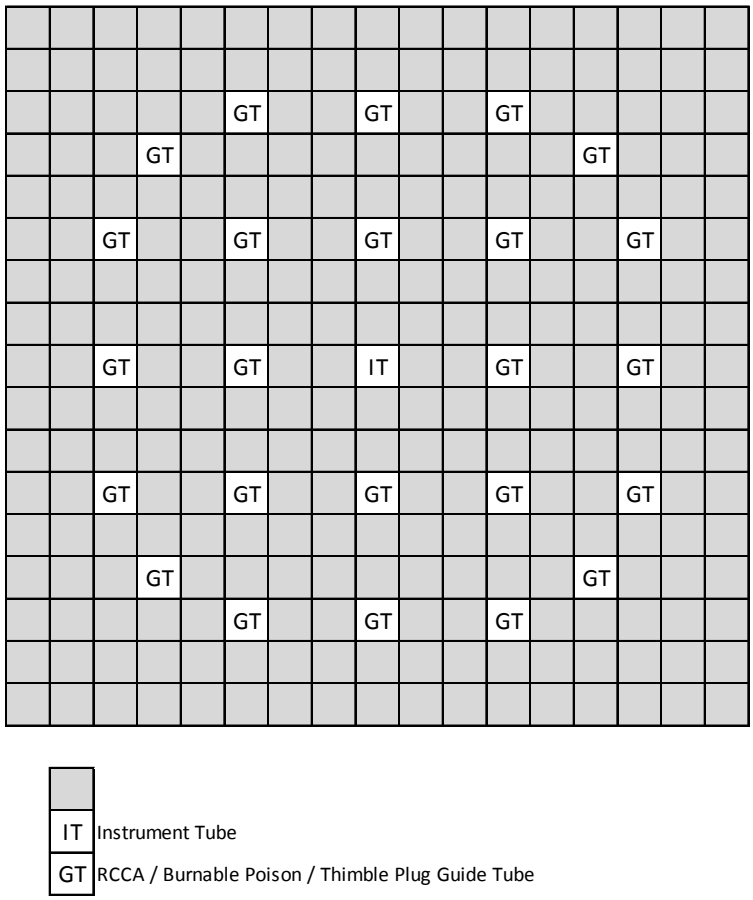



**Figure 3: 17x17 Lattice Fuel Rod and Thimble Arrangement**
(Ref. 1 Figure 4.2-1)

**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 | 21.5 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. 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 |
| Strap Material | Inconel-718 | Zircaloy-4 |
| Straps Mass (g) | 1017 | 875 |
| Spacer Sleeves Material | SS-304 | Zircaloy-4 |
| Spacer Sleeves Mass (g) | 91 | 74 |
| 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<br>388.2 | 75.2<br>127.4<br>179.6<br>231.8<br>284.0<br>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 obtained by the product of the material density and volumes given in Reference 8 (values based on OFA fuel). This data is not used in the reference solutions.
- 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 provides a pictorial of the assembly and provides some of its axial elevations. The specifications for the assembly are provided in Table 4 and specifications for the nozzles and core plates are given in Table 5.

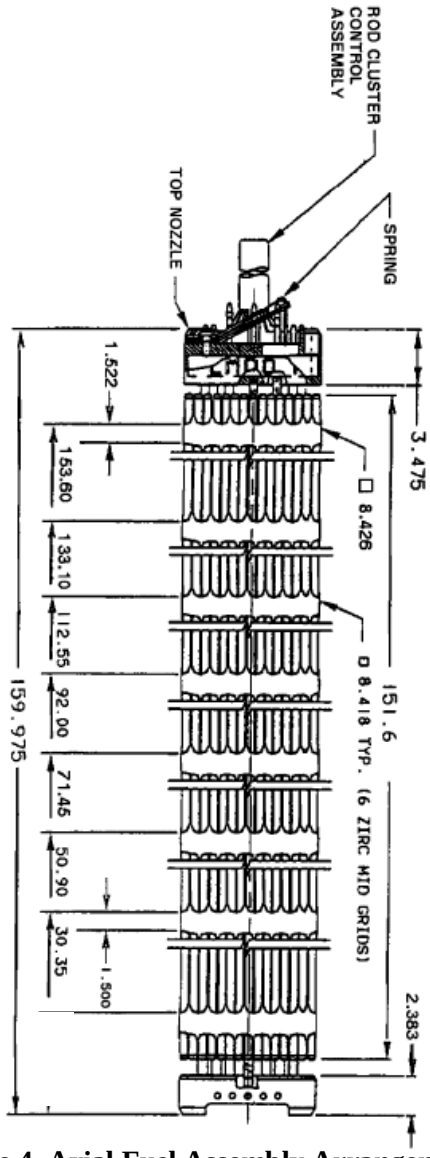



**Figure 4. Axial Fuel Assembly Arrangement**
(Ref. 1 Figure 4.2-2, in inches)

**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 dimensions shown in the drawing are approximate. The specifications are provided by the data in the tables, which may be based on the drawing data but may also be adjusted for consistency.

**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 | N/A | N/A |
| Height (cm) | 6.053 | 8.827 | 5.0 | 7.6 |
| Volume Fraction (%) | N/A | N/A | 50% | 50% |
| Axial Location (cm) (relative to top of lower core plate) | 0.0 | 397.51 | -5 | 406.337 |

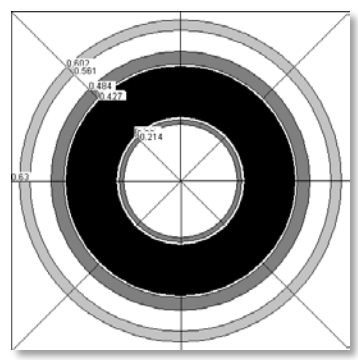
- The nozzle and core plate materials, heights, and axial locations are obtained from Ref. 1.
- The lower core plate thickness is obtained from Reference 9 for a generic Westinghouse plant.
- The upper core plate thickness is assumed. The model should be insensitive to this value.
- The nozzle masses are assumed to be equal, with an approximate total mass of 12.5 kgs. 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 wikipedia (www.wikipedia.com). These values are provided in the table below. For example, the mass fraction of B-10 in of $B_2O_3$-$SiO_2$, 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.

$$\rho_{pyrex} = 0.00624\ \frac{g\ B10}{cm} \times \frac{1}{\pi \times (0.427^2 - 0.241^2) cm^2} \times \frac{g\ pyrex}{0.00712\ g\ B10} = \mathbf{2.25}\ {}^{\boldsymbol{g}}/_{\boldsymbol{cc}}$$

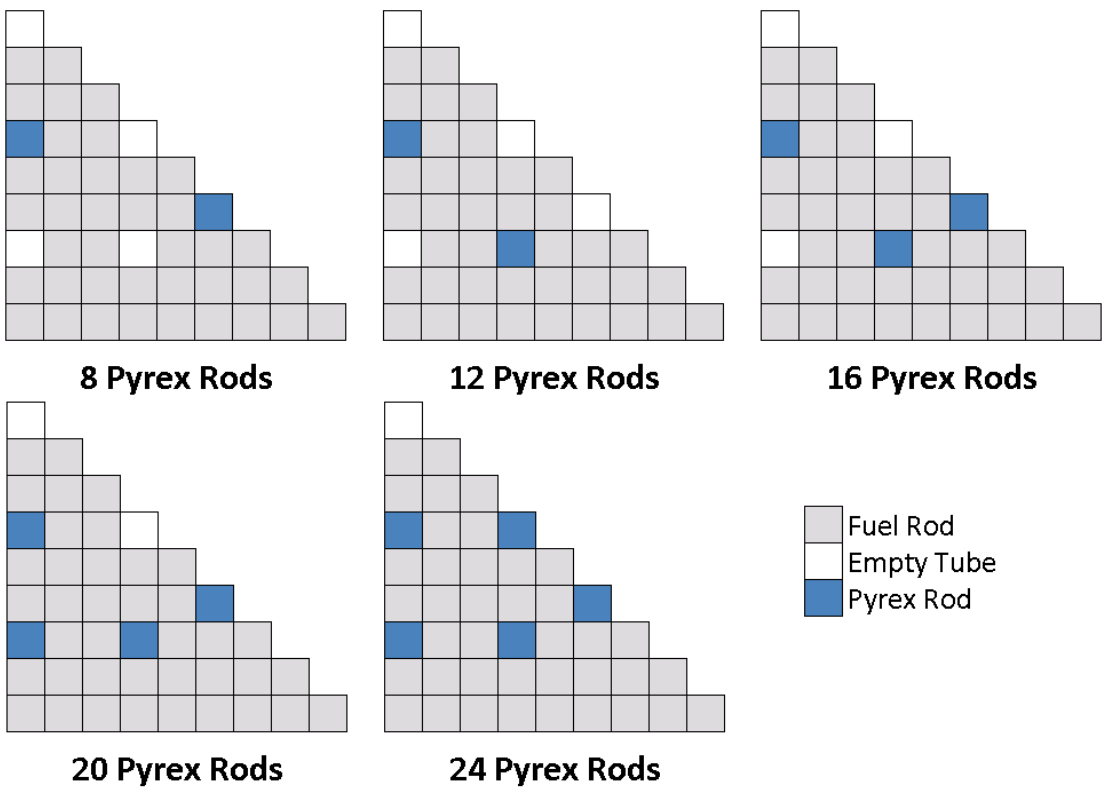



**Figure 5. Pyrex Configurations (Octant Symmetry)**
(Ref. 1 Figure 4.3-4)

## 1.6 CONTROL ROD GEOMETRY

WBN1C1 utilized hybrid $B_4C$ 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.

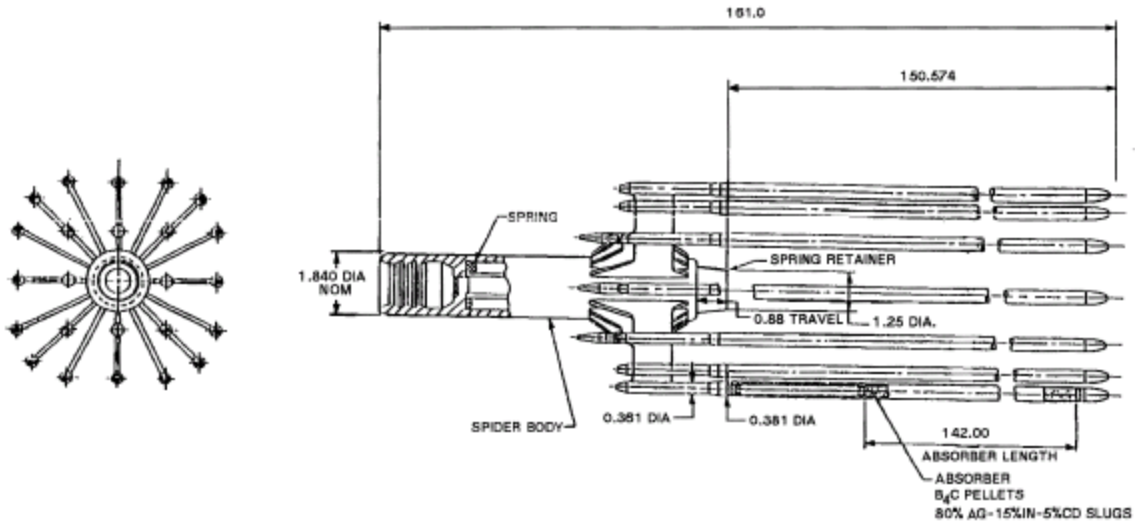
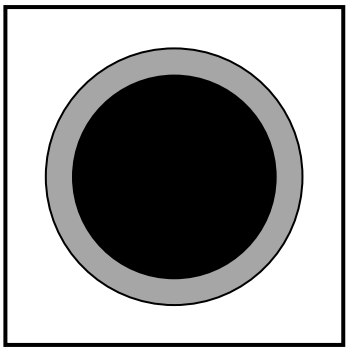



**Figure 6. RCCA Assembly**
(Ref. 1 Figure 4.2-15, in inches)

**Table 8: RCCA Rod and Drive Specification**

| Input | AIC | $B_4C$ |
|---|---|---|
| Composition | 80/15/5% Ag/In/Cd | 100% $B_4C$ |
| 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 rods. These are not typically modeled because the plugs are fairly short and do not reach the active fuel region. This data was obtained from Reference 1 and Reference 8.

**Table 9: Thimble Plug Specification**

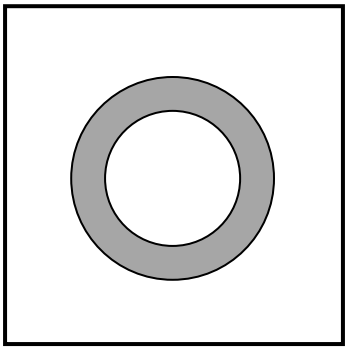
| Input | Value |
|---|---|
| Material | SS304 |
| Outer Radius | 0.538 cm |
| Height | 11.0 cm |
| Plenum Height | 22.2 cm |
| Axial Location | 383.31 cm |
| End Plug Height | ≈ 2.54 cm |

## 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 wikipedia (www.wikipedia.com). 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.

$$\rho_{ifba} = 2.355\ \frac{mg\ B10}{in} \times \frac{1\ in}{2.54\ cm} \times \frac{1\ g}{10^3\ mg} \times \frac{1}{\pi \times (0.4106^2 - 0.4096^2)\ cm^2} \times \frac{g\ ifba}{0.09347\ g\ B10} = \mathbf{3.85}\ {}^{\boldsymbol{g}}\!/_{\boldsymbol{cc}}$$

Alternately, the isotopic densities in units of atoms/bn-cm are provided in Table 12. The radial arrangement of the IFBA rods used in this document is 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 |

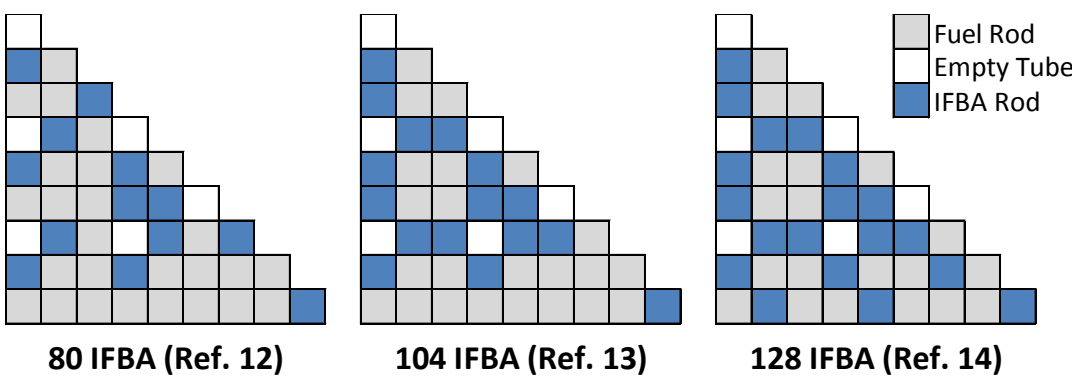


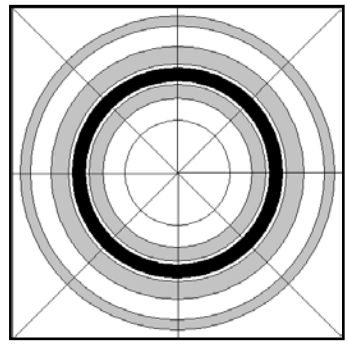

**Figure 7. IFBA Configurations (Octant Symmetry)**

## 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 |
| 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 wikipedia (www.wikipedia.com). 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 assumed to be the same as that of Pyrex shown in Figure 5. The 20 WABA layout is the same as shown in Reference 13.

## 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 with the $UO_2$ fuel pellets for a few select rods in the assembly in predetermined concentrations usually ranging from 2-8% by weight. This affects the fuel material density. 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.

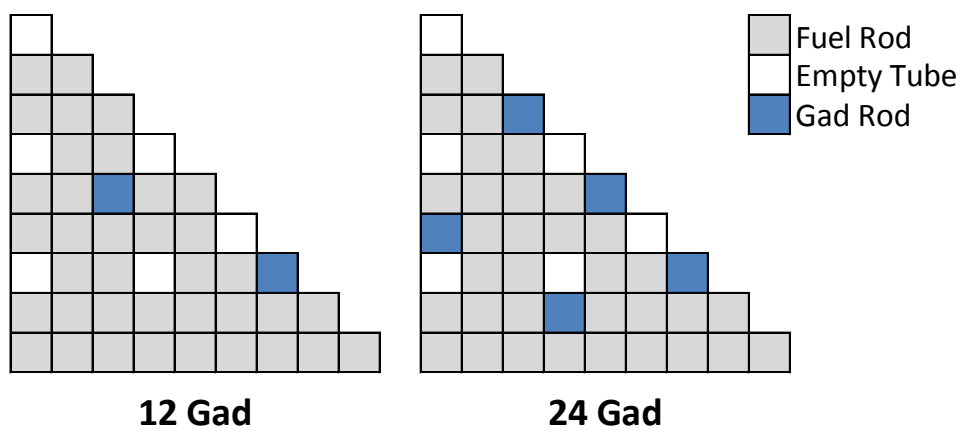



**Figure 8. Gadolinia Configurations (Octant Symmetry)**
(Ref. 15 p. 40)

## 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<br>20 | 2.1 | 2.6<br>20 | 2.1 | 2.6<br>20 | 2.1 | 3.1<br>12 |
| 9 | 2.6<br>20 | 2.1 | 2.6<br>24 | 2.1 | 2.6<br>20 | 2.1 | 3.1<br>24 | 3.1 |
| 10 | 2.1 | 2.6<br>24 | 2.1 | 2.6<br>20 | 2.1 | 2.6<br>16 | 2.1 | 3.1<br>8 |
| 11 | 2.6<br>20 | 2.1 | 2.6<br>20 | 2.1 | 2.6<br>20 | 2.1 | 3.1<br>16 | 3.1 |
| 12 | 2.1 | 2.6<br>20 | 2.1 | 2.6<br>20 | 2.6 | 2.6<br>24 | 3.1 | |
| 13 | 2.6<br>20 | 2.1 | 2.6<br>16 | 2.1 | 2.6<br>24 | 3.1<br>12 | 3.1 | |
| 14 | 2.1 | 3.1<br>24 | 2.1 | 3.1<br>16 | 3.1 | 3.1 | | |
| 15 | 3.1<br>12 | 3.1 | 3.1<br>8 | 3.1 | | | | |

Enrichment
Number of Pyrex Rods

**Figure 9. Core Fuel and Poison Loading Pattern (in 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 $B_4C$ 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 are not octant symmetric.

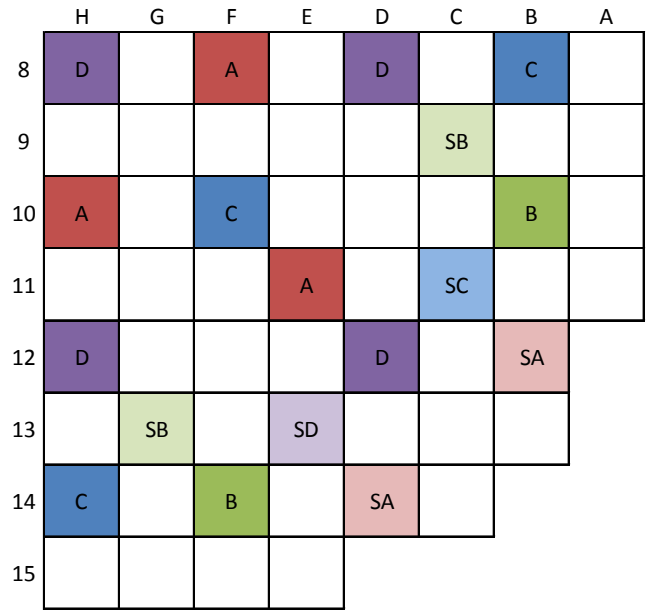



**Figure 10. Core RCCA Bank Positions (in quarter symmetry)**
(Ref. 1 Figure 4.3-36)

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 layout is not quarter symmetric.

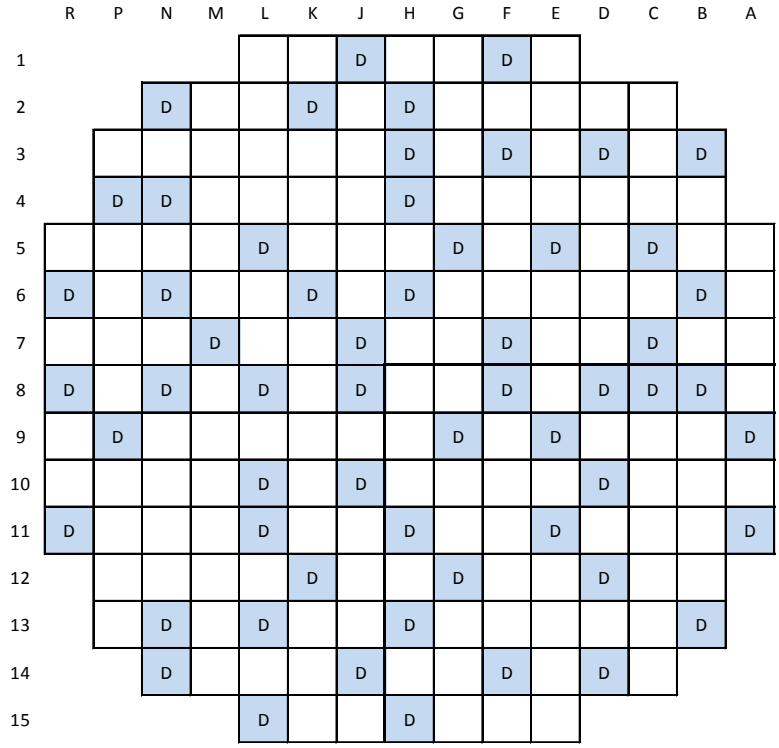



**Figure 11. Core Incore Instrumentation Locations**
(Ref. 1 Figure 4.4-22)

## 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.

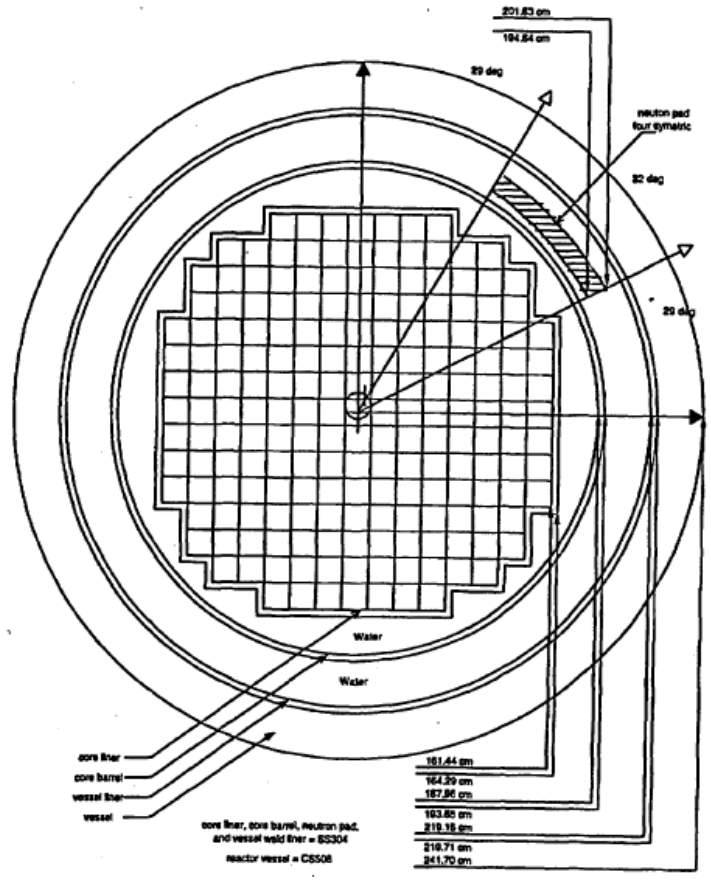



**Figure 12. Radial Core Structure**

(Ref. 8 Figure 2.1)

**Table 16: Core Structure Specification (Ref. 8)**

| Input | Value |
|---|---|
| Baffle Material | SS304 |
| Baffle Thickness | 2.85 cm |
| Gap between Fuel and Baffle | 0.19 cm |
| Barrel Material | SS304 |
| Barrel Inner Radius | 187.96 cm |
| Barrel Outer Radius | 193.68 cm |
| Neutron Pad Material | SS304 |
| Neutron Pad Inner Radius | 194.64 cm |
| Neutron Pad Outer Radius | 201.63 cm |
| Neutron Pad Arc Length | 32° |
| Neutron Pad Angular Location | 45° |
| Vessel Liner Material | SS304 |
| Vessel Liner Inner Radius | 219.15 cm |
| Vessel Material | CS508 |
| Vessel Inner Radius | 219.71 cm |
| Vessel 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 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 percent), ***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 realistic 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

The following items provide justification of certain conditions from WBN1 Cycle 1:

- The inlet coolant temperature is nominally 557.7 °F (Ref. 2), or **565 K**. HZP conditions are isothermal.
- The reactor pressure is nominally **2250 psi** (Ref. 2).
- The HZP BOC critical boron concentration is approximately **1300 ppmB** (Ref. 1).
- The average coolant temperature is nominally 592.8 °F (Ref. 2), or **585 K**.

# 4. CORE PHYSICS PROBLEMS

## Problem #1: 2D HZP BOC Pin Cell

### PURPOSE

The first AMA 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.

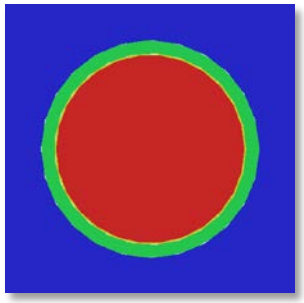


**Figure P1-1: Problem 1 KENO-VI Geometry**

### 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 constant 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 development version of the SCALE 6.2 (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 the SCALE 6.2 development version (**ce-v7-endf**) (Ref. 6). Both 565K and 600K cross sections are utilized.

### *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 (www.wikipedia.com). 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 $10^8$, skipping 250 generations. This limits the standard deviation in the resulting k-effective to approximately 8 pcm (actual uncertainties will be provided in the results). The development version of KENO-VI was used to provide parallel capability, which decreases run time and makes it much easier to use many more particle histories.

***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 the development version of SCALE 6.2 on cpile2.ornl.gov from location **/scale/scale_dev/staging-mpi**.

### *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 at 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 | Moderator Temperature | Fuel Temperature | Moderator Density | k-effective |
|---|---|---|---|---|
| **1A** | 565 K | 565 K | 0.743 g/cc | **1.187820 ± 0.000071** |
| **1B** | 600 K | 600 K | 0.661 g/cc | **1.182935 ± 0.000071** |
| **1C** | ↓ | 900 K | ↓ | **1.172386 ± 0.000075** |
| **1D** | ↓ | 1200K | ↓ | **1.163150 ± 0.000069** |
| **1E** | ↓ | 600 K | 0.743 g/cc | **0.772366 ± 0.000078** |

## Problem #2: 2D HZP BOC Fuel Lattice

### PURPOSE

The second AMA 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 (often referred to as 'pin powers') among the fuel rods.

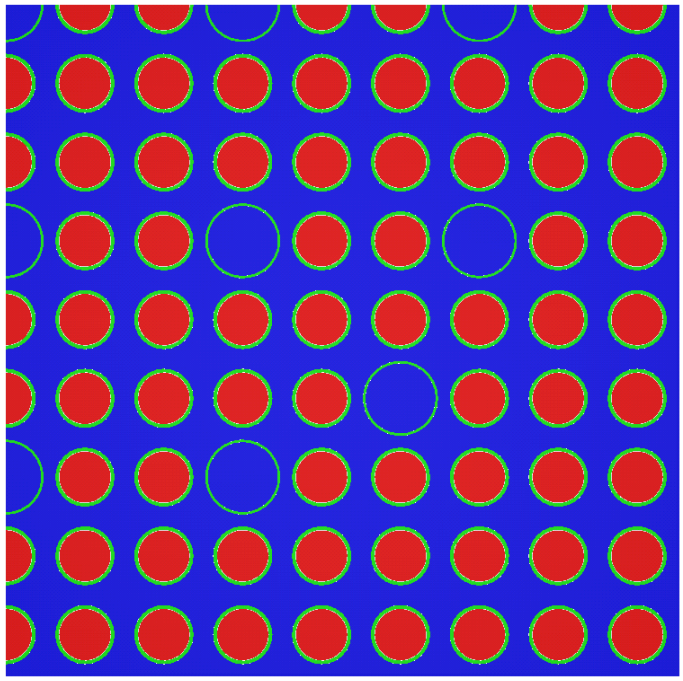


**Figure P2-1: Problem 2 KENO-VI Geometry**

### 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. Some 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. Input specifications are provided below in Tables P2-1, P2-2, and P2-3. Finally, 2Q tests a code's capability to accurately model the reactivity depression and radial power distribution produced by spacer grids.

**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.
- 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.

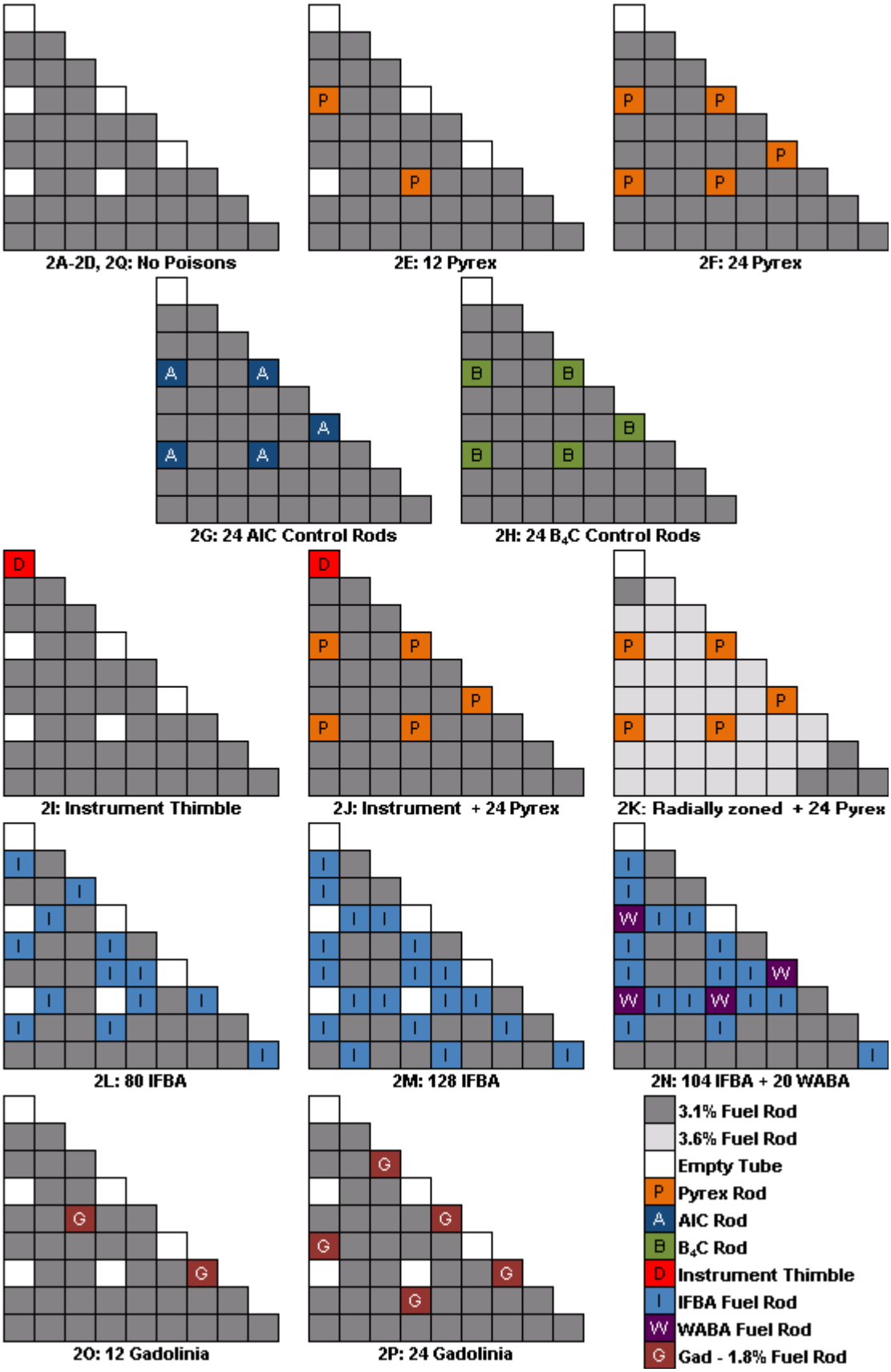



**Figure P2-2: Problem 2 Lattice Layouts (Octant Symmetry)**

## 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 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. KENO-VI input 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 the SCALE 6.2 development version (**ce-v7-endf**) (Ref. 6). Both 565K and 600K cross sections are utilized.

### *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 (www.wikipedia.com). 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.

### *Parameters*

In order to get the power distribution uncertainty as low as possible an extremely large number of particles must be used. In this case, 1e9 particles are used, skipping 250 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 P2-20 show the exact KENO-VI geometry for each of the problems.

### *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 24-80 processors for as little as six hours.

### *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 |

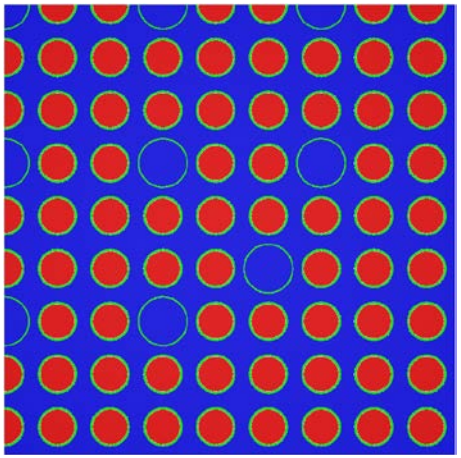
## REFERENCE SOLUTION RESULTS

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 | **1.182733 ± 0.000023** |
| **2B** | ↓ | 600 K | 0.661 g/cc | **1.184033 ± 0.000023** |
| **2C** | ↓ | 900 K | ↓ | **1.174434 ± 0.000022** |
| **2D** | ↓ | 1200 K | ↓ | **1.166137 ± 0.000022** |
| **2E** | 12 Pyrex | 600 K | 0.743 g/cc | **1.070441 ± 0.000025** |
| **2F** | 24 Pyrex | ↓ | ↓ | **0.976903 ± 0.000025** |
| **2G** | 24 AIC | ↓ | ↓ | **0.849236 ± 0.000024** |
| **2H** | 24 B4C | ↓ | ↓ | **0.789746 ± 0.000024** |
| **2I** | Instrument Thimble | ↓ | ↓ | **1.180561 ± 0.000024** |
| **2J** | Instrument + 24 Pyrex | ↓ | ↓ | **0.976101 ± 0.000024** |
| **2K** | Zoned + 24 Pyrex | ↓ | ↓ | **1.020999 ± 0.000024** |
| **2L** | 80 IFBA | ↓ | ↓ | **1.019538 ± 0.000024** |
| **2M** | 128 IFBA | ↓ | ↓ | **0.939462 ± 0.000025** |
| **2N** | 104 IFBA + 20 WABA | ↓ | ↓ | **0.870430 ± 0.000025** |
| **2O** | 12 Gadolinia | ↓ | ↓ | **1.048367 ± 0.000024** |
| **2P** | 24 Gadolinia | ↓ | ↓ | **0.927999 ± 0.000026** |
| **2Q** | Zircaloy Spacer Grid | 565 K | ↓ | **1.172614 ± 0.000023** |



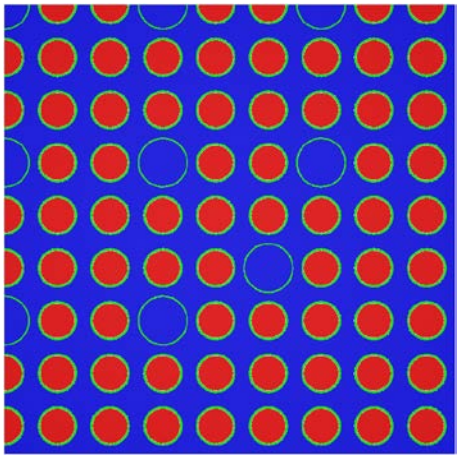
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.0358 | 1.0094 | | | | | | | |
| 1.0365 | 1.0094 | 1.0094 | | | | | | |
| | 1.0376 | 1.0390 | | | | | | |
| 1.0354 | 1.0080 | 1.0109 | 1.0455 | 1.0325 | | | | |
| 1.0318 | 1.0058 | 1.0094 | 1.0448 | 1.0513 | | | | |
| | 1.0257 | 1.0278 | | 1.0361 | 1.0170 | 0.9740 | | |
| 1.0116 | 0.9878 | 0.9888 | 1.0116 | 0.9834 | 0.9650 | 0.9488 | 0.9394 | |
| 0.9762 | 0.9719 | 0.9719 | 0.9737 | 0.9647 | 0.9549 | 0.9462 | 0.9426 | 0.9488 |

**Max: 1.0513 Min: 0.9394 Avg: 1.0000**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.034% | 0.041% | | | | | | | |
| 0.034% | 0.029% | 0.041% | | | | | | |
| | 0.029% | 0.029% | | | | | | |
| 0.034% | 0.029% | 0.029% | 0.029% | 0.041% | | | | |
| 0.034% | 0.029% | 0.029% | 0.029% | 0.029% | | | | |
| | 0.029% | 0.029% | | 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% |

**Max: 0.041% Min: 0.029% Avg: 0.031%**

**Figure P2-3: Problem 2A (565K) CE KENO-VI Power Distribution Results**



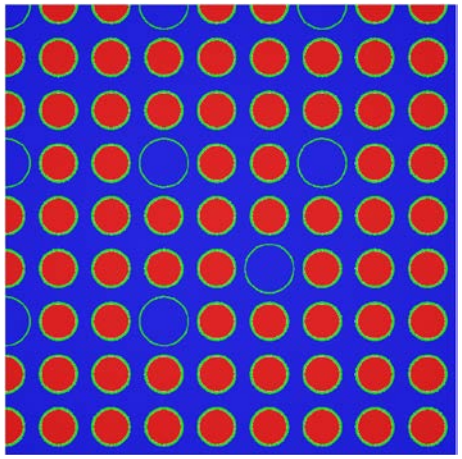
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.0353 | 1.0115 | | | | | | | |
| 1.0357 | 1.0115 | 1.0115 | | | | | | |
| | 1.0360 | 1.0371 | | | | | | |
| 1.0342 | 1.0101 | 1.0126 | 1.0429 | 1.0310 | | | | |
| 1.0313 | 1.0064 | 1.0097 | 1.0429 | 1.0476 | | | | |
| | 1.0245 | 1.0259 | | 1.0324 | 1.0144 | 0.9740 | | |
| 1.0104 | 0.9891 | 0.9891 | 1.0097 | 0.9837 | 0.9664 | 0.9498 | 0.9408 | |
| 0.9780 | 0.9743 | 0.9740 | 0.9754 | 0.9664 | 0.9567 | 0.9473 | 0.9433 | 0.9480 |

**Max: 1.0476 Min: 0.9408 Avg: 1.0000**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 0.021% | 0.021% | 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% |

**Max: 0.030% Min: 0.021% Avg: 0.023%**

**Figure P2-4: Problem 2B (600K) CE KENO-VI Power Distribution Results**



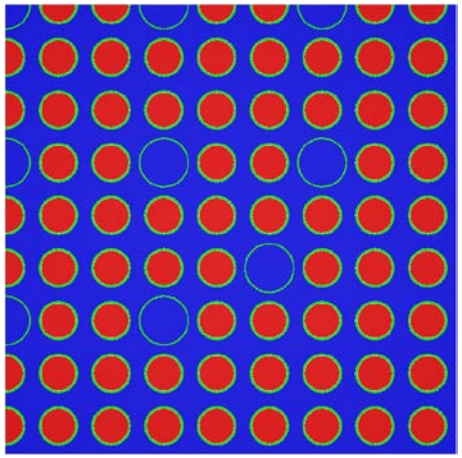
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.0358 | 1.0111 | | | | | | | |
| 1.0362 | 1.0115 | 1.0125 | | | | | | |
| | 1.0365 | 1.0373 | | | | | | |
| 1.0340 | 1.0100 | 1.0125 | 1.0427 | 1.0307 | | | | |
| 1.0311 | 1.0067 | 1.0096 | 1.0424 | 1.0475 | | | | |
| | 1.0245 | 1.0256 | | 1.0329 | 1.0147 | 0.9740 | | |
| 1.0107 | 0.9889 | 0.9889 | 1.0100 | 0.9838 | 0.9660 | 0.9503 | 0.9405 | |
| 0.9780 | 0.9744 | 0.9733 | 0.9754 | 0.9667 | 0.9569 | 0.9471 | 0.9427 | 0.9478 |

Max: 1.0475 Min: 0.9405 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 0.021% | 0.021% | 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% |

Max: 0.030% Min: 0.021% Avg: 0.023%

**Figure P2-5: Problem 2C (900K) CE KENO-VI Power Distribution Results**



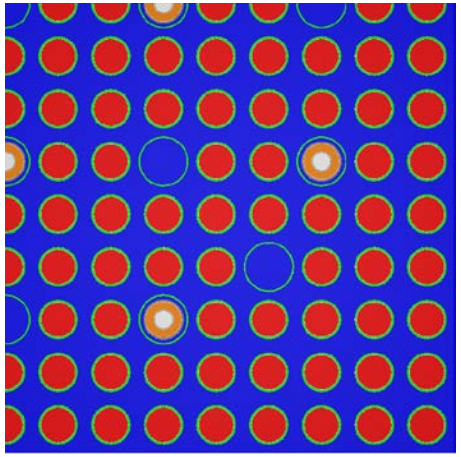
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.0367 | 1.0117 | | | | | | | |
| 1.0359 | 1.0117 | 1.0125 | | | | | | |
| | 1.0367 | 1.0374 | | | | | | |
| 1.0341 | 1.0095 | 1.0125 | 1.0429 | 1.0308 | | | | |
| 1.0315 | 1.0066 | 1.0095 | 1.0421 | 1.0473 | | | | |
| | 1.0246 | 1.0260 | | 1.0330 | 1.0147 | 0.9736 | | |
| 1.0106 | 0.9890 | 0.9890 | 1.0103 | 0.9839 | 0.9660 | 0.9498 | 0.9407 | |
| 0.9784 | 0.9740 | 0.9736 | 0.9751 | 0.9656 | 0.9564 | 0.9476 | 0.9429 | 0.9480 |

Max: 1.0473 Min: 0.9407 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 0.021% | 0.021% | 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% |

Max: 0.030% Min: 0.021% Avg: 0.023%

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



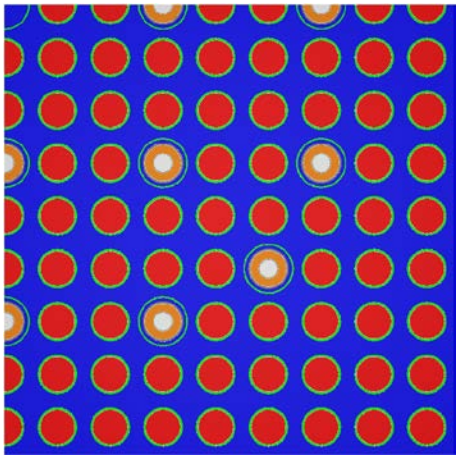
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.0175 | 0.9923 | | | | | | | |
| 0.9297 | 0.9632 | 0.9963 | | | | | | |
| | 0.9324 | 1.0251 | | | | | | |
| 0.9352 | 0.9692 | 1.0027 | 1.0370 | 1.0282 | | | | |
| 1.0282 | 1.0031 | 0.9748 | 0.9516 | 1.0231 | | | | |
| | 1.0354 | 0.9424 | | 0.9580 | 1.0430 | 1.0322 | | |
| 1.0586 | 1.0219 | 0.9768 | 0.9348 | 0.9788 | 1.0143 | 1.0239 | 1.0298 | |
| 1.0350 | 1.0235 | 1.0059 | 0.9939 | 1.0055 | 1.0211 | 1.0318 | 1.0398 | 1.0514 |

Max: 1.0586 Min: 0.9297 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 0.021% | 0.021% | 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% |

Max: 0.030% Min: 0.021% Avg: 0.023%

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



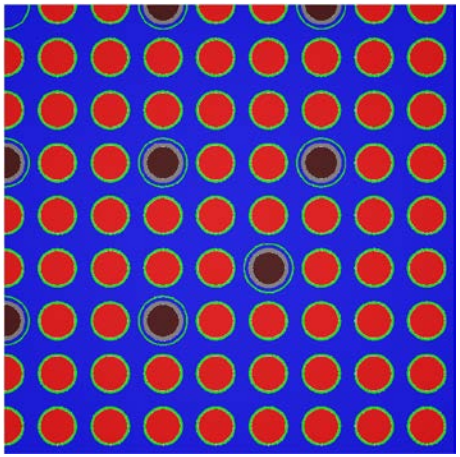
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.0769 | 1.0418 | | | | | | | |
| 0.9718 | 0.9911 | 0.9736 | | | | | | |
| | 0.9333 | 0.9263 | | | | | | |
| 0.9263 | 0.9591 | 0.9547 | 0.9118 | 0.9263 | | | | |
| 0.9280 | 0.9617 | 0.9587 | 0.9127 | 0.9070 | | | | |
| | 0.9420 | 0.9412 | | 0.9355 | 0.9670 | 1.0340 | | |
| 0.9749 | 1.0046 | 1.0059 | 0.9788 | 1.0191 | 1.0502 | 1.0821 | 1.1093 | |
| 1.0484 | 1.0532 | 1.0554 | 1.0554 | 1.0720 | 1.0917 | 1.1132 | 1.1338 | 1.1539 |

Max: 1.1539 Min: 0.9070 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 0.021% | 0.021% | 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% |

Max: 0.030% Min: 0.021% Avg: 0.023%

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



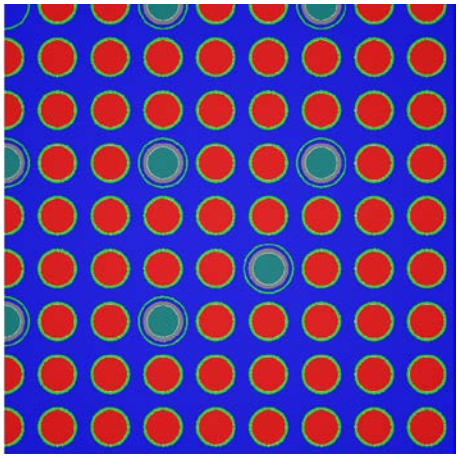
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.0742 | 1.0354 | | | | | | | |
| 0.9395 | 0.9661 | 0.9412 | | | | | | |
| | 0.8855 | 0.8767 | | | | | | |
| 0.8735 | 0.9203 | 0.9148 | 0.8536 | 0.8724 | | | | |
| 0.8789 | 0.9269 | 0.9215 | 0.8560 | 0.8511 | | | | |
| | 0.9089 | 0.9077 | | 0.9067 | 0.9648 | 1.0707 | | |
| 0.9644 | 1.0061 | 1.0092 | 0.9778 | 1.0389 | 1.0949 | 1.1519 | 1.1987 | |
| 1.0707 | 1.0803 | 1.0858 | 1.0893 | 1.1201 | 1.1579 | 1.1997 | 1.2350 | 1.2653 |

Max: 1.2653 Min: 0.8511 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.035% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.035% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.035% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 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% |

Max: 0.035% Min: 0.021% Avg: 0.023%

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



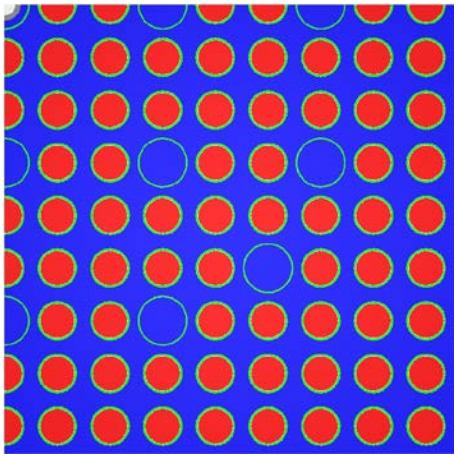
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.0607 | 1.0214 | | | | | | | |
| 0.9223 | 0.9487 | 0.9220 | | | | | | |
| | 0.8648 | 0.8550 | | | | | | |
| 0.8517 | 0.9000 | 0.8937 | 0.8315 | 0.8513 | | | | |
| 0.8594 | 0.9093 | 0.9034 | 0.8367 | 0.8345 | | | | |
| | 0.8964 | 0.8962 | | 0.9025 | 0.9712 | 1.0895 | | |
| 0.9612 | 1.0045 | 1.0100 | 0.9806 | 1.0493 | 1.1145 | 1.1828 | 1.2403 | |
| 1.0760 | 1.0863 | 1.0939 | 1.1014 | 1.1400 | 1.1872 | 1.2376 | 1.2816 | 1.3174 |

Max: 1.3174 Min: 0.8315 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.035% | 0.030% | | | | | | | |
| 0.035% | 0.021% | 0.030% | | | | | | |
| | 0.028% | 0.021% | | | | | | |
| 0.035% | 0.021% | 0.025% | 0.028% | 0.040% | | | | |
| 0.035% | 0.021% | 0.021% | 0.028% | 0.028% | | | | |
| | 0.021% | 0.025% | | 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% |

Max: 0.040% Min: 0.021% Avg: 0.025%

**Figure P2-10: Problem 2H ($B_4C$) CE KENO-VI Power Distribution Results**



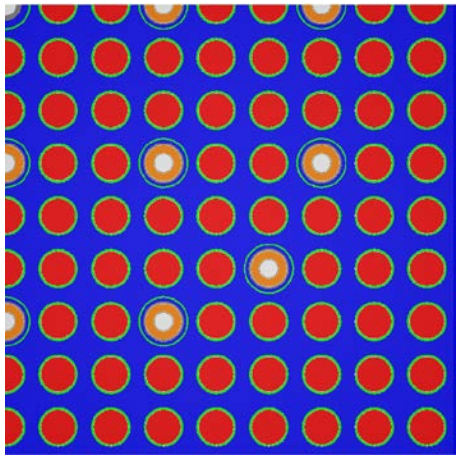
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.0050 | 0.9923 | | | | | | | |
| 1.0256 | 1.0024 | 1.0068 | | | | | | |
| | 1.0343 | 1.0372 | | | | | | |
| 1.0350 | 1.0086 | 1.0119 | 1.0455 | 1.0328 | | | | |
| 1.0328 | 1.0068 | 1.0097 | 1.0458 | 1.0520 | | | | |
| | 1.0270 | 1.0288 | | 1.0372 | 1.0187 | 0.9757 | | |
| 1.0133 | 0.9902 | 0.9902 | 1.0126 | 0.9855 | 0.9670 | 0.9507 | 0.9410 | |
| 0.9789 | 0.9746 | 0.9742 | 0.9764 | 0.9674 | 0.9576 | 0.9486 | 0.9449 | 0.9497 |

Max: 1.0520 Min: 0.9410 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 0.021% | 0.021% | 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% |

Max: 0.030% Min: 0.021% Avg: 0.023%

**Figure P2-11: Problem 2I (Instrument Thimble) CE KENO-VI Power Distribution Results**



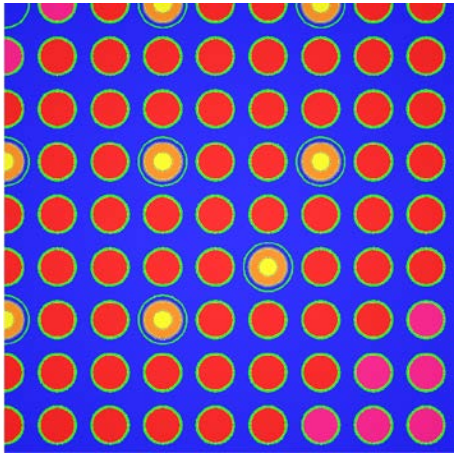
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.0409 | 1.0234 | | | | | | | |
| 0.9594 | 0.9822 | 0.9691 | | | | | | |
| | 0.9301 | 0.9253 | | | | | | |
| 0.9261 | 0.9594 | 0.9559 | 0.9130 | 0.9279 | | | | |
| 0.9288 | 0.9629 | 0.9594 | 0.9139 | 0.9082 | | | | |
| | 0.9437 | 0.9428 | | 0.9371 | 0.9691 | 1.0365 | | |
| 0.9757 | 1.0063 | 1.0076 | 0.9813 | 1.0212 | 1.0523 | 1.0847 | 1.1119 | |
| 1.0497 | 1.0554 | 1.0580 | 1.0580 | 1.0742 | 1.0944 | 1.1154 | 1.1356 | 1.1557 |

Max: 1.1557 Min: 0.9082 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.032% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 0.021% | 0.021% | 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% |

Max: 0.032% Min: 0.021% Avg: 0.023%

**Figure P2-12: Problem 2J (Instrument and Pyrex) CE KENO-VI Power Distribution Results**



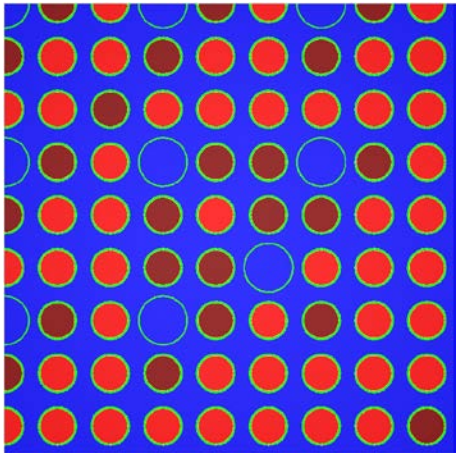
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.9768 | 1.0627 | | | | | | | |
| 0.9894 | 1.0049 | 0.9856 | | | | | | |
| | 0.9459 | 0.9387 | | | | | | |
| 0.9375 | 0.9689 | 0.9655 | 0.9237 | 0.9387 | | | | |
| 0.9387 | 0.9710 | 0.9681 | 0.9249 | 0.9195 | | | | |
| | 0.9513 | 0.9509 | | 0.9471 | 0.9806 | 1.0501 | | |
| 0.9814 | 1.0108 | 1.0116 | 0.9877 | 1.0288 | 1.0644 | 1.1071 | 1.0149 | |
| 1.0518 | 1.0581 | 1.0606 | 1.0623 | 1.0811 | 1.1092 | 1.0149 | 1.0447 | 1.0685 |

Max: 1.1092 Min: 0.9195 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 0.021% | 0.021% | 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% |

Max: 0.030% Min: 0.021% Avg: 0.023%

**Figure P2-13: Problem 2K (Zoned and 24 Pyrex) CE KENO-VI Power Distribution Results**



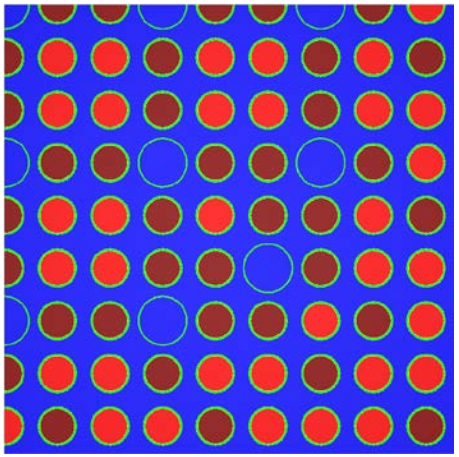
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.9483 | 0.9970 | | | | | | | |
| 1.0326 | 1.0003 | 0.9307 | | | | | | |
| | 0.9559 | 1.0288 | | | | | | |
| 0.9601 | 1.0091 | 1.0108 | 0.9408 | 0.9819 | | | | |
| 1.0477 | 1.0217 | 1.0163 | 0.9400 | 0.9391 | | | | |
| | 0.9693 | 1.0465 | | 0.9542 | 1.0330 | 0.9391 | | |
| 0.9643 | 1.0196 | 1.0276 | 0.9651 | 1.0154 | 1.0230 | 1.0096 | 1.0079 | |
| 1.0305 | 1.0364 | 1.0372 | 1.0305 | 1.0339 | 1.0351 | 1.0259 | 1.0024 | 0.9047 |

Max: 1.0477 Min: 0.9047 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 0.021% | 0.021% | 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% |

Max: 0.030% Min: 0.021% Avg: 0.023%

**Figure P2-14: Problem 2L (80 IFBA) CE KENO-VI Power Distribution Results**



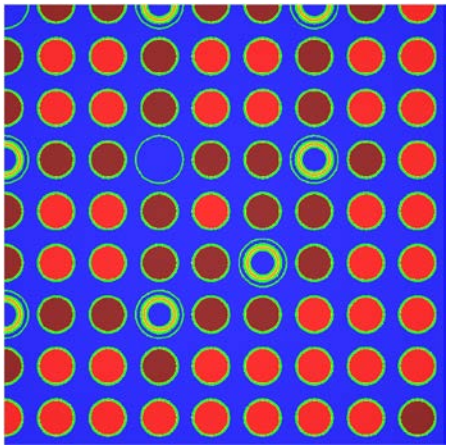
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.9835 | 1.0390 | | | | | | | |
| 0.9835 | 1.0390 | 1.0390 | | | | | | |
| | 0.9835 | 0.9821 | | | | | | |
| 0.9826 | 1.0372 | 1.0363 | 0.9762 | 1.0208 | | | | |
| 0.9812 | 1.0363 | 1.0345 | 0.9712 | 0.9698 | | | | |
| | 0.9780 | 0.9775 | | 0.9698 | 0.9662 | 1.0044 | | |
| 0.9730 | 1.0194 | 1.0304 | 0.9789 | 1.0172 | 1.0162 | 0.9439 | 1.0153 | |
| 1.0071 | 0.9434 | 1.0335 | 1.0290 | 0.9470 | 1.0322 | 1.0363 | 1.0299 | 0.9416 |

Max: 1.0390 Min: 0.9416 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 0.021% | 0.021% | 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% |

Max: 0.030% Min: 0.021% Avg: 0.023%

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



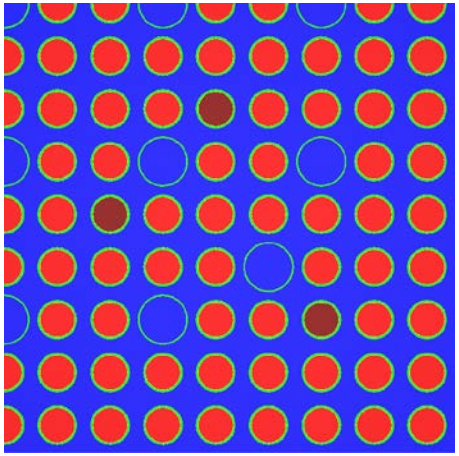
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.9754 | 1.0268 | | | | | | | |
| 0.8997 | 0.9963 | 1.0219 | | | | | | |
| | 0.8920 | 0.9660 | | | | | | |
| 0.8699 | 0.9719 | 1.0057 | 0.9468 | 0.9556 | | | | |
| 0.8673 | 0.9644 | 0.9698 | 0.8652 | 0.8464 | | | | |
| | 0.8820 | 0.8827 | | 0.8701 | 0.9109 | 1.0553 | | |
| 0.9248 | 1.0155 | 1.0185 | 0.9315 | 1.0362 | 1.0824 | 1.1276 | 1.1537 | |
| 1.0809 | 1.0927 | 1.0962 | 1.0922 | 1.1188 | 1.1458 | 1.1665 | 1.1606 | 1.0593 |

Max: 1.1665 Min: 0.8464 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.035% | 0.030% | | | | | | | |
| 0.035% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.035% | 0.021% | 0.021% | 0.021% | 0.030% | | | | |
| 0.035% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 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% |

Max: 0.035% Min: 0.021% Avg: 0.023%

**Figure P2-16: Problem 2N (104 IFBA + 20 WABA) CE KENO-VI Power Distribution Results**



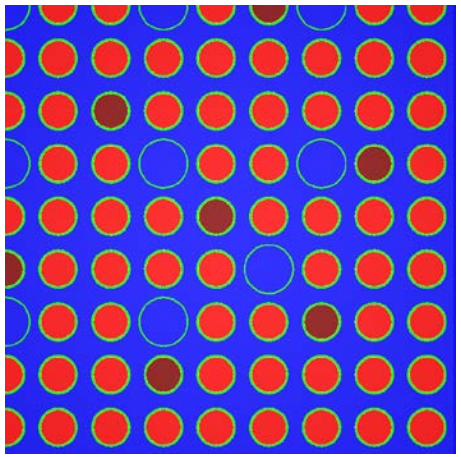
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.1058 | 1.0704 | | | | | | | |
| 1.0883 | 1.0504 | 1.0182 | | | | | | |
| | 1.0414 | 0.9807 | | | | | | |
| 1.0471 | 0.9652 | 0.2168 | 0.9880 | 1.0369 | | | | |
| 1.0740 | 1.0227 | 0.9770 | 1.0557 | 1.0814 | | | | |
| | 1.0928 | 1.0826 | | 1.0793 | 0.9929 | 0.2167 | | |
| 1.1050 | 1.0773 | 1.0732 | 1.0920 | 1.0471 | 0.9925 | 0.9253 | 0.9636 | |
| 1.0781 | 1.0712 | 1.0675 | 1.0638 | 1.0435 | 1.0166 | 0.9929 | 0.9998 | 1.0174 |

Max: 1.1058 Min: 0.2167 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.030% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.035% | 0.021% | 0.030% | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 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% |

Max: 0.050% Min: 0.021% Avg: 0.024%

**Figure P2-17: Problem 2O (12 Gadolinia) CE KENO-VI Power Distribution Results**



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 1.1680 | 1.1109 | | | | | | | |
| 1.1418 | 1.0533 | 0.2432 | | | | | | |
| | 1.1183 | 1.0639 | | | | | | |
| 1.0662 | 1.0828 | 1.0878 | 1.0629 | 0.2433 | | | | |
| 0.2450 | 1.0404 | 1.0957 | 1.1086 | 1.0606 | | | | |
| | 1.1146 | 1.1067 | | 1.0809 | 1.0381 | 0.2422 | | |
| 1.1478 | 1.1090 | 1.0330 | 0.2432 | 1.0076 | 1.0408 | 1.0053 | 1.0611 | |
| 1.1335 | 1.1146 | 1.0648 | 0.9952 | 1.0436 | 1.0749 | 1.0818 | 1.1053 | 1.1302 |

Max: 1.1680 Min: 0.2422 Avg: 1.0000

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| 0.028% | 0.030% | | | | | | | |
| 0.028% | 0.021% | 0.050% | | | | | | |
| | 0.021% | 0.021% | | | | | | |
| 0.028% | 0.021% | 0.021% | 0.021% | 0.050% | | | | |
| 0.057% | 0.021% | 0.021% | 0.021% | 0.021% | | | | |
| | 0.021% | 0.021% | | 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% |

Max: 0.057% Min: 0.021% Avg: 0.025%

**Figure P2-18: Problem 2P (24 Gadolinia) CE KENO-VI Power Distribution Results**

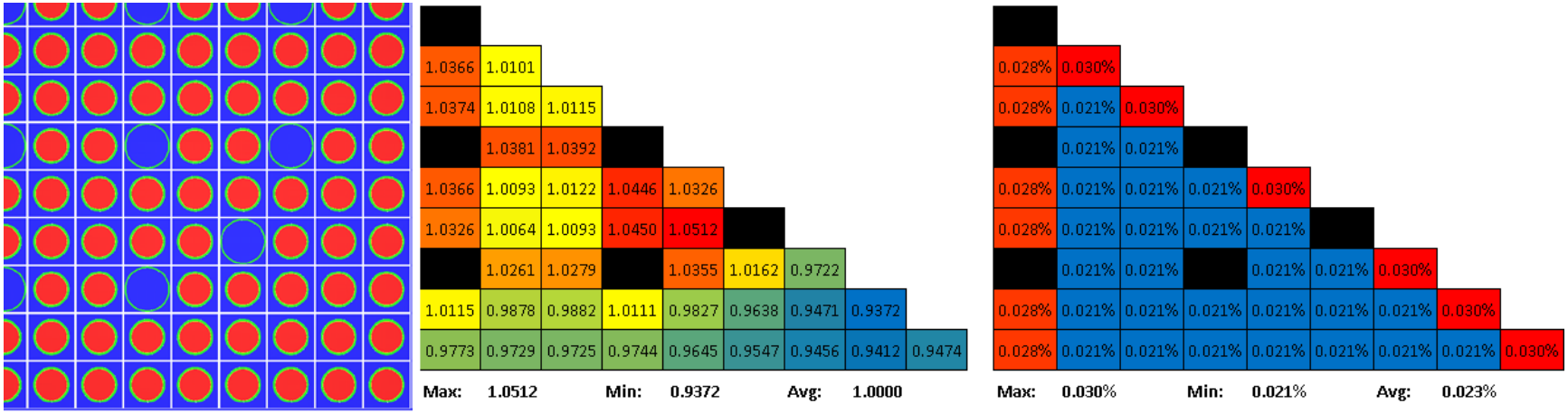



**Figure P2-19: Problem 2Q (Zircaloy Spacer Grid) CE KENO-VI Power Distribution Results**

## 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.
- 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.
- For 3B, the boron concentration of 1066 was chosen to make this problem close to critical (eigenvalue = 1.0).

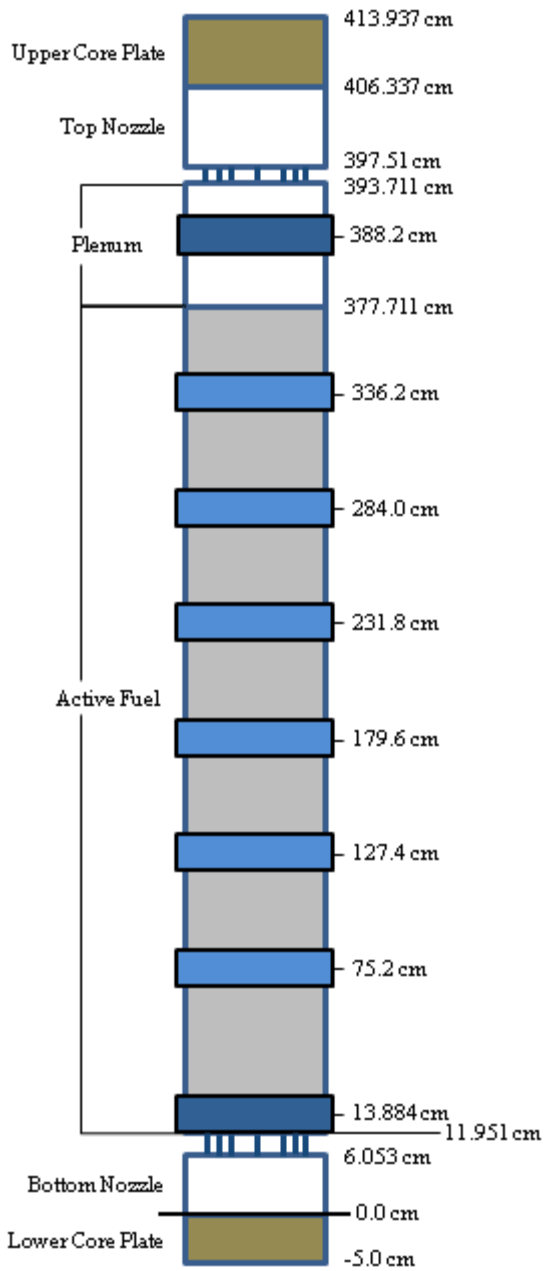



**Figure P3-1: Problem 3 Axial Geometry (without end plugs)**

## 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 (Dev) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The development version was used because the problem size requires CPU parallelization for a practical turnaround time and to get the power distribution uncertainty low enough to be acceptable. KENO-VI input 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. 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 CE cross sections as obtained from the SCALE 6.2 component CENTRM (**ce-v7-endf**) (Ref. 6). Both 565K and 600K cross sections are utilized.

### *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 | 3.1% | 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 (www.wikipedia.com). 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 place was homogenized manually based on the material densities and heights. These materials are provided in the mixing table below. The KENO input for the weight fraction of each material is rounded to four digits, which results in a small amount of error. Furthermore, the materials were not modified for changing boron concentrations. Because of the large amount of metal mass in these regions, the B-10 makes up less than 0.05% of the region by mass. This effect is expected to be insignificant.

***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 $5.5e^9$ produces less than 1 pcm uncertainty in the eigenvalue and less than 0.1% uncertainty in pin power.

***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, but 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.

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 will be provided with the reference solution data.

Figure P3-1 provides a 3D graphical view of problem 3A, using KENO-3D.

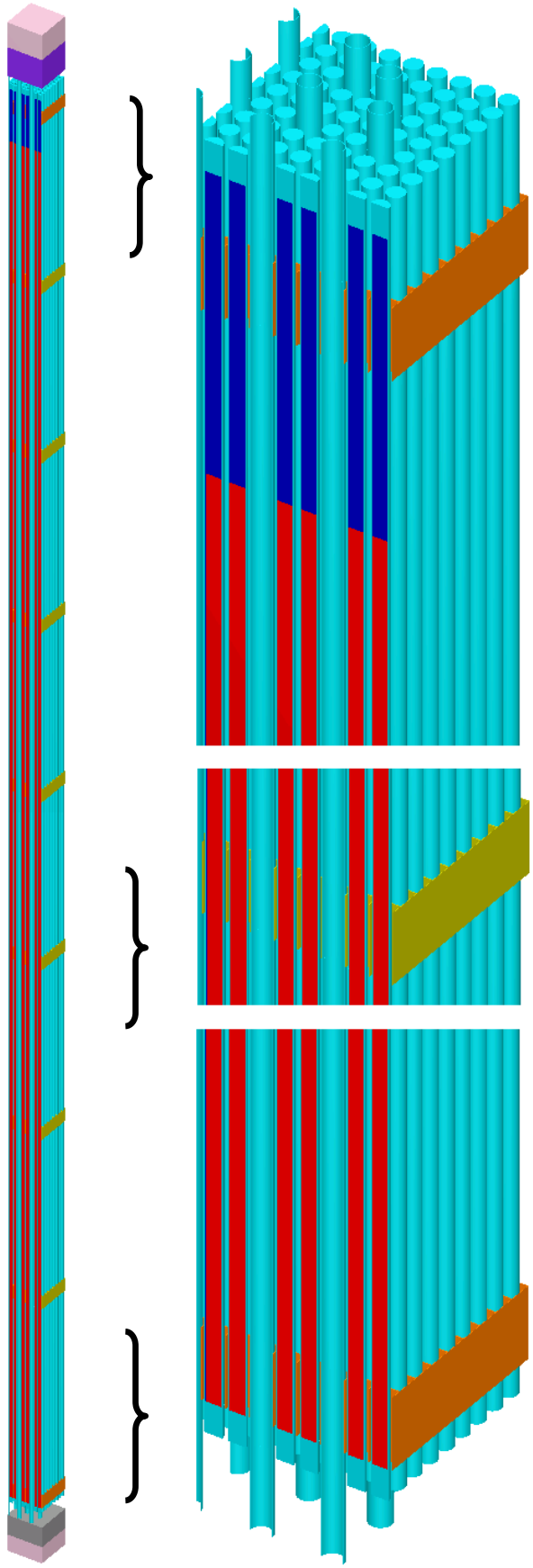


**Figure P3-2: Problem 3 Reference Model**

### *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 the development version of SCALE 6.2 on cpile2.ornl.gov from location **/scale/scale_dev/staging-mpi**.

### *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) |
|---|---|---|
| **3.1% 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 |
| **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 |
| **Top Nozzle** | 1001 | 4.00685E-02 |
| | 5010 | 9.44445E-06 |
| | 5011 | 3.80151E-05 |
| | 6000 | 6.13703E-05 |
| | 8016 | 2.00342E-02 |
| | 14028 | 3.02547E-04 |
| | 14029 | 1.53696E-05 |
| | 14030 | 1.01436E-05 |
| | 15031 | 1.33861E-05 |
| | 24050 | 1.46288E-04 |
| | 24052 | 2.82102E-03 |
| | 24053 | 3.19881E-04 |
| | 24054 | 7.96251E-05 |
| | 25055 | 3.35423E-04 |
| | 26054 | 6.59376E-04 |
| | 26056 | 1.03508E-02 |

| | | |
|---|---|---|
| | 26057 | 2.39045E-04 |
| | 26058 | 3.18125E-05 |
| | 28058 | 1.01525E-03 |
| | 28060 | 3.91071E-04 |
| | 28061 | 1.69996E-05 |
| | 28062 | 5.42021E-05 |
| | 28064 | 1.38037E-05 |
| **Bottom Nozzle** | 1001 | 3.57697E-02 |
| | 5010 | 9.21166E-06 |
| | 5011 | 3.70781E-05 |
| | 6000 | 8.96212E-05 |
| | 8016 | 1.78849E-02 |
| | 14028 | 4.41821E-04 |
| | 14029 | 2.24448E-05 |
| | 14030 | 1.48131E-05 |
| | 15031 | 1.95482E-05 |
| | 24050 | 2.13630E-04 |
| | 24052 | 4.11963E-03 |
| | 24053 | 4.67133E-04 |
| | 24054 | 1.16279E-04 |
| | 25055 | 4.89830E-04 |
| | 26054 | 9.62909E-04 |
| | 26056 | 1.51156E-02 |
| | 26057 | 3.49086E-04 |
| | 26058 | 4.64569E-05 |
| | 28058 | 1.48260E-03 |
| | 28060 | 5.71094E-04 |
| | 28061 | 2.48251E-05 |
| | 28062 | 7.91532E-05 |
| | 28064 | 2.01580E-05 |
| **Core Plates** | 1001 | 2.48109E-02 |
| | 5010 | 4.84416E-06 |
| | 5011 | 1.94983E-05 |
| | 6000 | 1.60389E-04 |
| | 8016 | 1.24055E-02 |
| | 14028 | 7.90698E-04 |
| | 14029 | 4.01681E-05 |
| | 14030 | 2.65101E-05 |
| | 15031 | 3.49842E-05 |
| | 24050 | 3.82319E-04 |
| | 24052 | 7.37264E-03 |
| | 24053 | 8.35998E-04 |
| | 24054 | 2.08098E-04 |
| | 25055 | 8.76618E-04 |
| | 26054 | 1.72326E-03 |
| | 26056 | 2.70514E-02 |
| | 26057 | 6.24736E-04 |
| | 26058 | 8.31409E-05 |
| | 28058 | 2.65331E-03 |
| | 28060 | 1.02205E-03 |
| | 28061 | 4.44278E-05 |
| | 28062 | 1.41655E-04 |
| | 28064 | 3.60754E-05 |
| **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 |
| | 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

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

**Table P3-4: Problem 3 Reference Solution Eigenvalue Results**

| Problem | Description | Enrichment | Boron | Temperature | k-effective |
|---|---|---|---|---|---|
| **3A** | No Poisons | 3.1% | 1300 ppm | 600K | **1.176286 ± 0.000010** |
| **3B** | 16 Pyrex | 2.619% | 1066 ppm | 565K | **1.001532 ± 0.000010** |

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 1D and 2D power shapes will be provided in a later revision, as new tools come available for these visualizations.

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

## PURPOSE

The fourth AMA core physics benchmark progression problem builds on the 3D assembly problem by the addition of multiple assemblies, RCCAs, and Pyrex burnable absorbers. 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 2.1% enrichment with center RCCA, and Region 2 is the 2.619% enriched region with the 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.

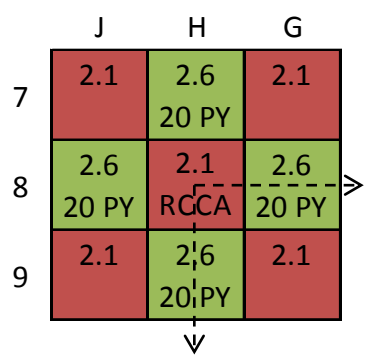



**Figure P4-1: Problem 4 Assembly, Poison, and Control Layout**

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 critical position of Problem 5. The other eleven cases for Problem 4 for are for RCCA positions spacing 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 rods 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.
- The moderator density corresponds to 565K at the core pressure. (Reference 4).
- The 20 Pyrex pattern (Section 1.5) should ideally use 4 thimble plugs in the remaining empty guide tubes, though this is not likely to affect the neutronics solution significantly.
- 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 (Dev) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The development version was used because the problem size requires CPU parallelization for a practical turnaround

time and to get the power distribution uncertainty low enough to be acceptable. KENO-VI input 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 (~500,000 lines). This code is located at **/home/agm/git/kenogen**.

### *Cross Sections*

The reference solution is based on ENDF/B-VII CE cross sections as obtained from the SCALE 6.2 component CENTRM (**ce-v7-endf**) (Ref. 6). Only 565K cross sections are utilized.

### *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 (www.wikipedia.com). 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 place was homogenized manually based on the material densities and heights. These materials are provided in the mixing table below. The KENO input for the weight fraction of each material is rounded to four digits, which results in a small amount of error. Furthermore, the materials are based on the Problem 3A boron concentration of 1300 ppm. Because of the large amount of metal mass in these regions, the B-10 makes up less than 0.05% of the region by mass. This effect is expected to be insignificant.

### *Parameters*

A very large number of particle histories is needed to get the power distribution uncertainty low enough to be useful for comparison with other codes, especially in the regions of lowest power. In this case $12e^9$ produces less than 1 pcm uncertainty in the eigenvalue and less than 0.131% uncertainty in average pin power. This is only for the first case. The rod worth cases were used only

for reactivity, not pin power distribution, so these cases only used 250e6 particles and resulted in an eigenvalue uncertainty of less than 6 pcm.

***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.

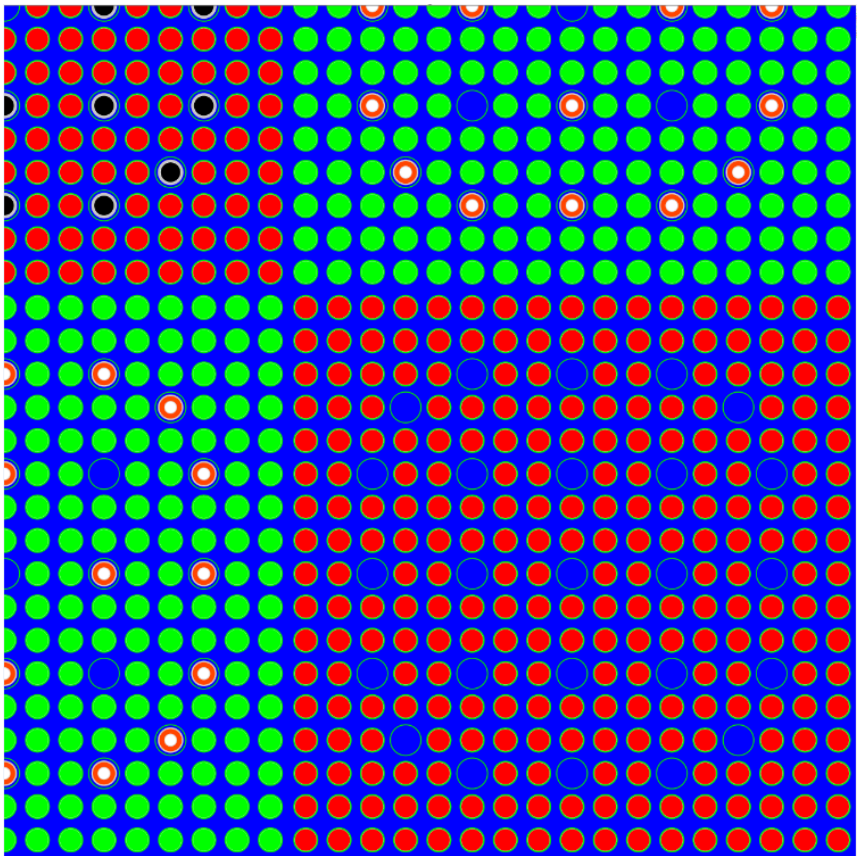


**Figure P4-2: Problem 4 Radial KENO-VI Geometry**

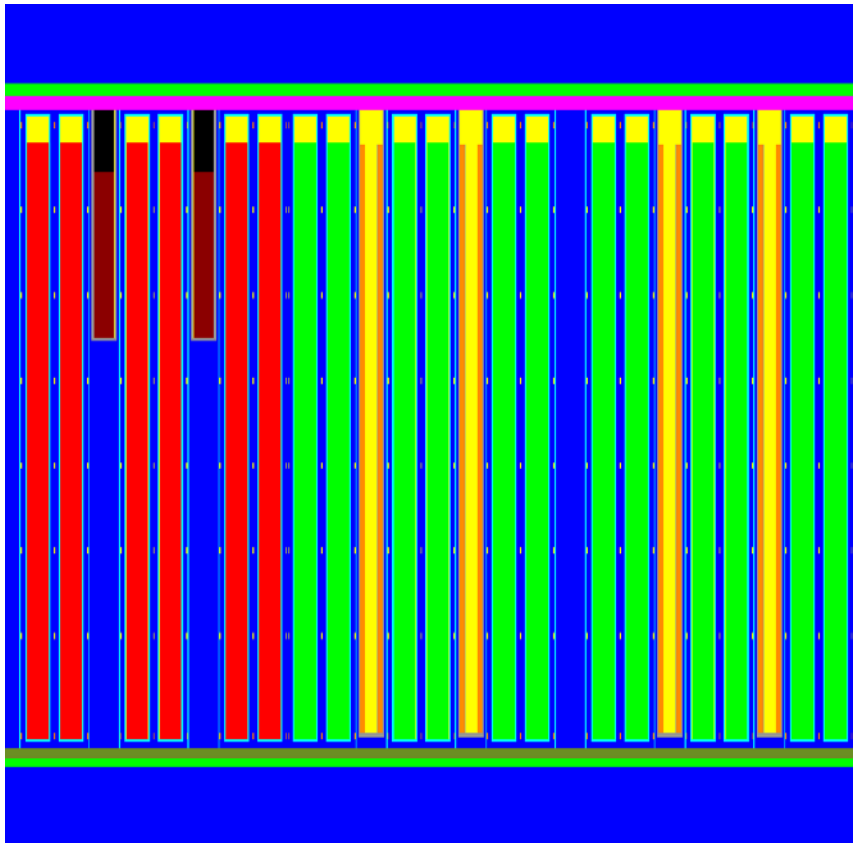


**Figure P4-3: Problem 4 Axial KENO-VI Geometry (not to proportion)**

### *Input File*

The input for this problem is nearly 500,000 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 the development version of SCALE 6.2 on cpile2.ornl.gov from location **/scale/scale_dev/staging-mpi**.

### *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) |
|---|---|---|
| **2.1% 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 |
| | 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 | 4.00685E-02 |
| | 5010 | 9.44445E-06 |
| | 5011 | 3.80151E-05 |
| | 6000 | 6.13703E-05 |
| | 8016 | 2.00342E-02 |
| | 14028 | 3.02547E-04 |
| | 14029 | 1.53696E-05 |
| | 14030 | 1.01436E-05 |
| | 15031 | 1.33861E-05 |
| | 24050 | 1.46288E-04 |
| | 24052 | 2.82102E-03 |
| | 24053 | 3.19881E-04 |
| | 24054 | 7.96251E-05 |
| | 25055 | 3.35423E-04 |
| | 26054 | 6.59376E-04 |
| | 26056 | 1.03508E-02 |
| | 26057 | 2.39045E-04 |
| | 26058 | 3.18125E-05 |
| | 28058 | 1.01525E-03 |
| | 28060 | 3.91071E-04 |

| | | |
|---|---|---|
| | 28061 | 1.69996E-05 |
| | 28062 | 5.42021E-05 |
| | 28064 | 1.38037E-05 |
| **Bottom Nozzle** | 1001 | 3.57697E-02 |
| | 5010 | 9.21166E-06 |
| | 5011 | 3.70781E-05 |
| | 6000 | 8.96212E-05 |
| | 8016 | 1.78849E-02 |
| | 14028 | 4.41821E-04 |
| | 14029 | 2.24448E-05 |
| | 14030 | 1.48131E-05 |
| | 15031 | 1.95482E-05 |
| | 24050 | 2.13630E-04 |
| | 24052 | 4.11963E-03 |
| | 24053 | 4.67133E-04 |
| | 24054 | 1.16279E-04 |
| | 25055 | 4.89830E-04 |
| | 26054 | 9.62909E-04 |
| | 26056 | 1.51156E-02 |
| | 26057 | 3.49086E-04 |
| | 26058 | 4.64569E-05 |
| | 28058 | 1.48260E-03 |
| | 28060 | 5.71094E-04 |
| | 28061 | 2.48251E-05 |
| | 28062 | 7.91532E-05 |
| | 28064 | 2.01580E-05 |
| **Core Plates** | 1001 | 2.48109E-02 |
| | 5010 | 4.84416E-06 |
| | 5011 | 1.94983E-05 |
| | 6000 | 1.60389E-04 |
| | 8016 | 1.24055E-02 |
| | 14028 | 7.90698E-04 |
| | 14029 | 4.01681E-05 |
| | 14030 | 2.65101E-05 |
| | 15031 | 3.49842E-05 |
| | 24050 | 3.82319E-04 |
| | 24052 | 7.37264E-03 |
| | 24053 | 8.35998E-04 |
| | 24054 | 2.08098E-04 |
| | 25055 | 8.76618E-04 |
| | 26054 | 1.72326E-03 |
| | 26056 | 2.70514E-02 |
| | 26057 | 6.24736E-04 |
| | 26058 | 8.31409E-05 |
| | 28058 | 2.65331E-03 |
| | 28060 | 1.02205E-03 |
| | 28061 | 4.44278E-05 |
| | 28062 | 1.41655E-04 |
| | 28064 | 3.60754E-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 |
| **B4C** | 5010 | 1.52689E-02 |
| | 5011 | 6.14591E-02 |
| | 6000 | 1.91820E-02 |
| **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 |

## 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 Eigenvalue Results**

| Rod Position | % Withdrawn | k-effective | DRW (pcm) | IRW (pcm) |
|---|---|---|---|---|
| **257.9 cm** | **--** | **0.9999594 ± 0.0000069** | **--** | |
| 0 steps | 0% | **0.973446 ± 0.000052** | **-130 ± 7** | **-2970 ± 7** |
| 23 steps | 10% | **0.974677 ± 0.000047** | **-582 ± 7** | **-2841 ± 7** |
| 46 steps | 20% | **0.980233 ± 0.000055** | **-797 ± 8** | **-2259 ± 8** |
| 69 steps | 30% | **0.987952 ± 0.000055** | **-541 ± 8** | **-1462 ± 8** |
| 92 steps | 40% | **0.993259 ± 0.000051** | **-347 ± 7** | **-921 ± 7** |
| 115 steps | 50% | **0.996699 ± 0.000049** | **-226 ± 7** | **-574 ± 7** |
| 138 steps | 60% | **0.998951 ± 0.000047** | **-153 ± 7** | **-347 ± 7** |
| 161 steps | 70% | **1.000485 ± 0.000050** | **-110 ± 7** | **-194 ± 7** |
| 184 steps | 80% | **1.001588 ± 0.000047** | **-55 ± 7** | **-84 ± 7** |
| 207 steps | 90% | **1.002136 ± 0.000054** | **-29 ± 7** | **-29 ± 7** |
| 230 steps | 100% | **1.002431 ± 0.000047** | **--** | **--** |

Figures of these results are shown in Figure P4-4 and P4-5.

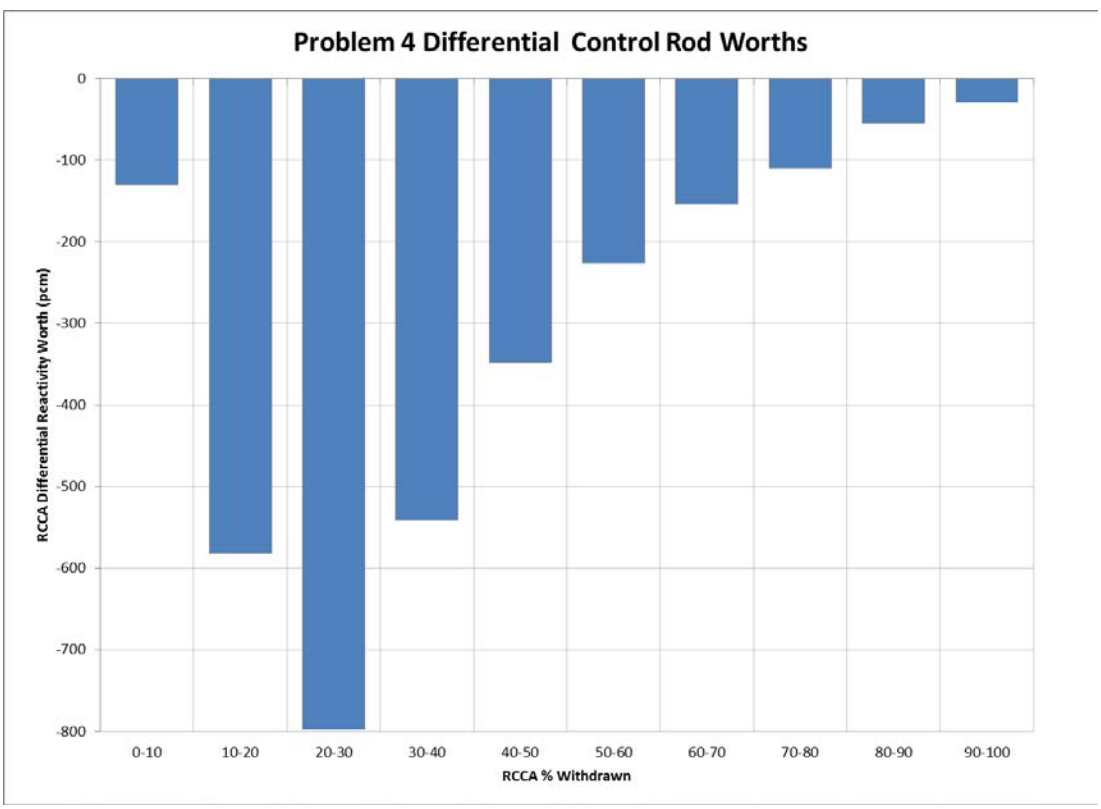



**Figure P4-4: Problem 4 Differential Control Rod Worth**

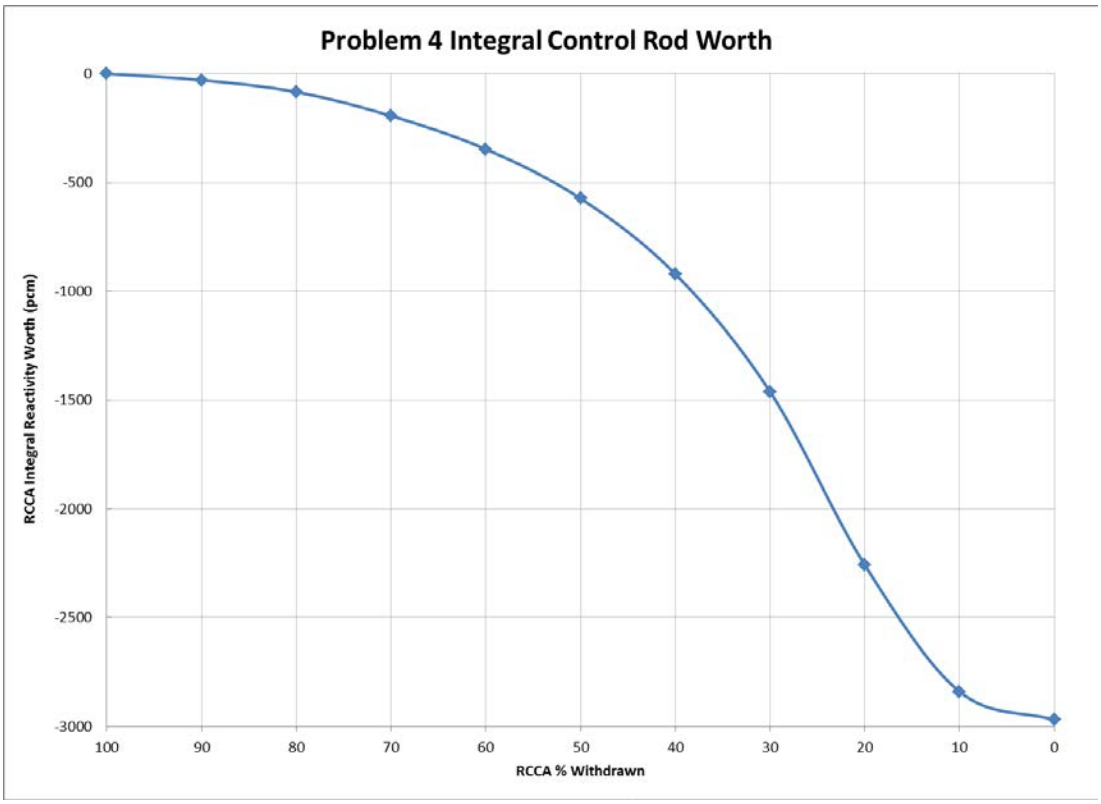



**Figure P4-5: Problem 4 Integral Control Rod Worth**

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 1D and 2D power shapes will be provided in a later revision, as new tools come available for these visualizations.

## Problem #5: Physical Reactor Zero Power Physics Tests

### PURPOSE

The fifth AMA core physics benchmark progression problem builds 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.

### 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 2.1% enrichment, and Region 2 is the 2.619% enriched region, and Region 3 is 3.1% enriched. Figures 9-12 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.

| | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|
| 8 | 2.1 | 2.6<br>20 | 2.1 | 2.6<br>20 | 2.1 | 2.6<br>20 | 2.1 | 3.1<br>12 |
| 9 | 2.6<br>20 | 2.1 | 2.6<br>24 | 2.1 | 2.6<br>20 | 2.1 | 3.1<br>24 | 3.1 |
| 10 | 2.1 | 2.6<br>24 | 2.1 | 2.6<br>20 | 2.1 | 2.6<br>16 | 2.1 | 3.1<br>8 |
| 11 | 2.6<br>20 | 2.1 | 2.6<br>20 | 2.1 | 2.6<br>20 | 2.1 | 3.1<br>16 | 3.1 |
| 12 | 2.1 | 2.6<br>20 | 2.1 | 2.6<br>20 | 2.6 | 2.6<br>24 | 3.1 | |
| 13 | 2.6<br>20 | 2.1 | 2.6<br>16 | 2.1 | 2.6<br>24 | 3.1<br>12 | 3.1 | |
| 14 | 2.1 | 3.1<br>24 | 2.1 | 3.1<br>16 | 3.1 | 3.1 | | |
| 15 | 3.1<br>12 | 3.1 | 3.1<br>8 | 3.1 | | | | |

Enrichment
Number of Pyrex Rods

**Figure P5-1: Problem 5 Assembly and Poison Layout in Quarter Symmetry**

The reference cases for Problem 5 involve a series of different control rod bank positions, soluble boron concentrations, and temperatures to support the physics parameter calculations. The first case is a simulation of core critical with Bank D (regulating bank) at 167 steps withdrawn. The other cases for Problem 5 all described in the table below. Bank positions used are 0, 230, and 110 steps withdrawn, with positions calculated from the information in Table 8 as:

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

**Table P5-1: 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 |
| Fuel Enrichment – Region 3 | 3.1% | 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. |
| 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.
- The moderator density corresponds to 565K at the core pressure. (Reference 4).

## 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 (Dev) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). The development version was used because the problem size requires CPU parallelization for a practical turnaround time and to get the power distribution uncertainty low enough to be acceptable. KENO-VI input 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 utilize enough particles to reduce the estimate fission rate uncertainty to acceptable levels in every location in the core model. At this time, only the core reactivity is utilized in this specification.

### *Cross Sections*

The reference solution is based on ENDF/B-VII CE cross sections as obtained from the SCALE 6.2 component CENTRM (**ce-v7-endf**) (Ref. 6). Only 565K cross sections are utilized.

### *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 P5-2: 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% | 3.1000% |
| **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 (www.wikipedia.com). 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. Other concentrations are calculated similarly.
- The material content for the top and bottom nozzles and top and bottom core place was homogenized manually based on the material densities and heights. These materials are provided in the mixing table below. The KENO input for the weight fraction of each material is rounded to four digits, which results in a small amount of error. Furthermore, the materials are based on the boron concentration of 1300 ppm, and are not changed for other concentrations. Because of the large amount of metal mass in these regions, the B-10 makes up less than 0.05% of the region by mass. This effect is expected to be insignificant.
- The neutron pads are assumed to be at the same axial location and height of the active fuel.

### *Parameters*

For the reactor criticality case, $250e^6$ produces less than 11 pcm uncertainty in the core eigenvalue. In this case reduced pin power uncertainties are not even attempted, so not as many particle histories are needed as in the previous problems. For many of reactivity coefficient calculations, reduced numbers of particles are used, and these uncertainties are documented in the results below.

***Geometry***

The geometry is modeled as explicitly as possible as described in Sections 1.1 to 1.13. Some of these details are enumerated below.

1. Explicit representation of fuel rod stack, plenum, and end plugs. The end plugs are assumed to be square cylinders of the prescribed length, and do not account for tapering of the ends or other geometric detail. This end plus treatment also applies to RCCAs, pyrex rods, and thimble plugs.
2. 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 in a box on the outside of each cell. The spacer grid spacer sleeves are ignored
3. 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.
4. Homogenization of the top and bottom nozzles of each assembly.
5. Explicit modeling of pyrex and RCCA stacks, axial locations, end plugs, and plenum regions below the top nozzle. RCCA geometry in and above the top nozzle is ignored. Fully withdrawn RCCAs are also included in the model up to the upper nozzle.
6. Explicit inclusion of thimble plugs in upper regions of guide tubes which do not contain RCCA rodlets or pyrex rodlets.
7. 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 reactivity.
8. Exclusion of primary and secondary source rods (Ref. 1)
9. Explicit treatment of the core baffle assuming solid stainless steel.
10. Homogenization of upper and lower core plates assuming 50% coolant volume fraction.
11. Inclusion of core support structure and containers such as the neutron pads, core barrel, vessel liner, and the carbon steel vessel itself.
12. 50 cm axial buffer of moderator between the core plates and axial vacuum boundary to assure proper calculation of the core axial leakage.

Figure P5-2 provides a radial view of a slice through the middle of the Problem 5 quarter core geometry. Figure P5-3 provides an axial view.

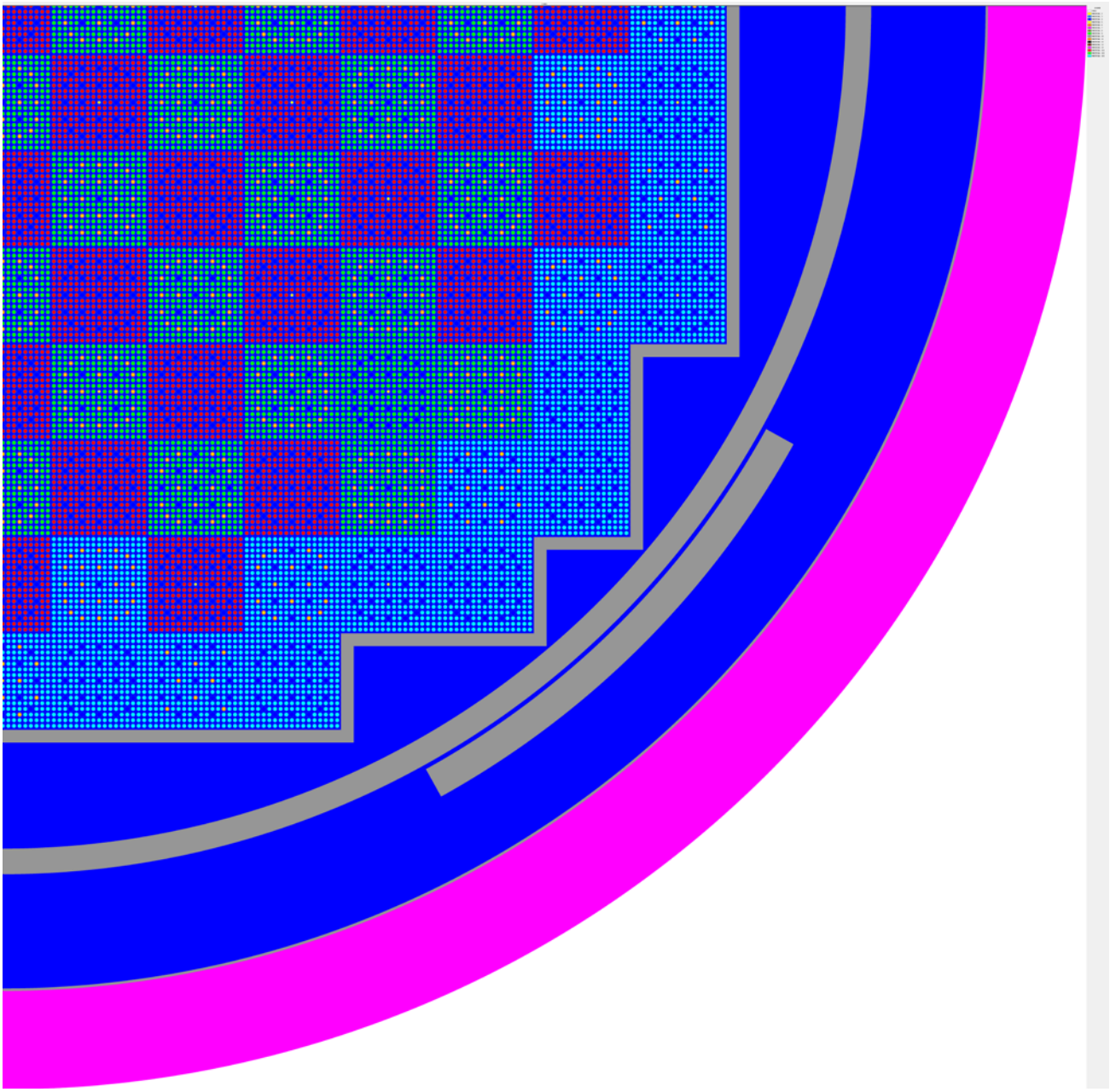


**Figure P5-2: Problem 5 Radial KENO-VI Geometry**

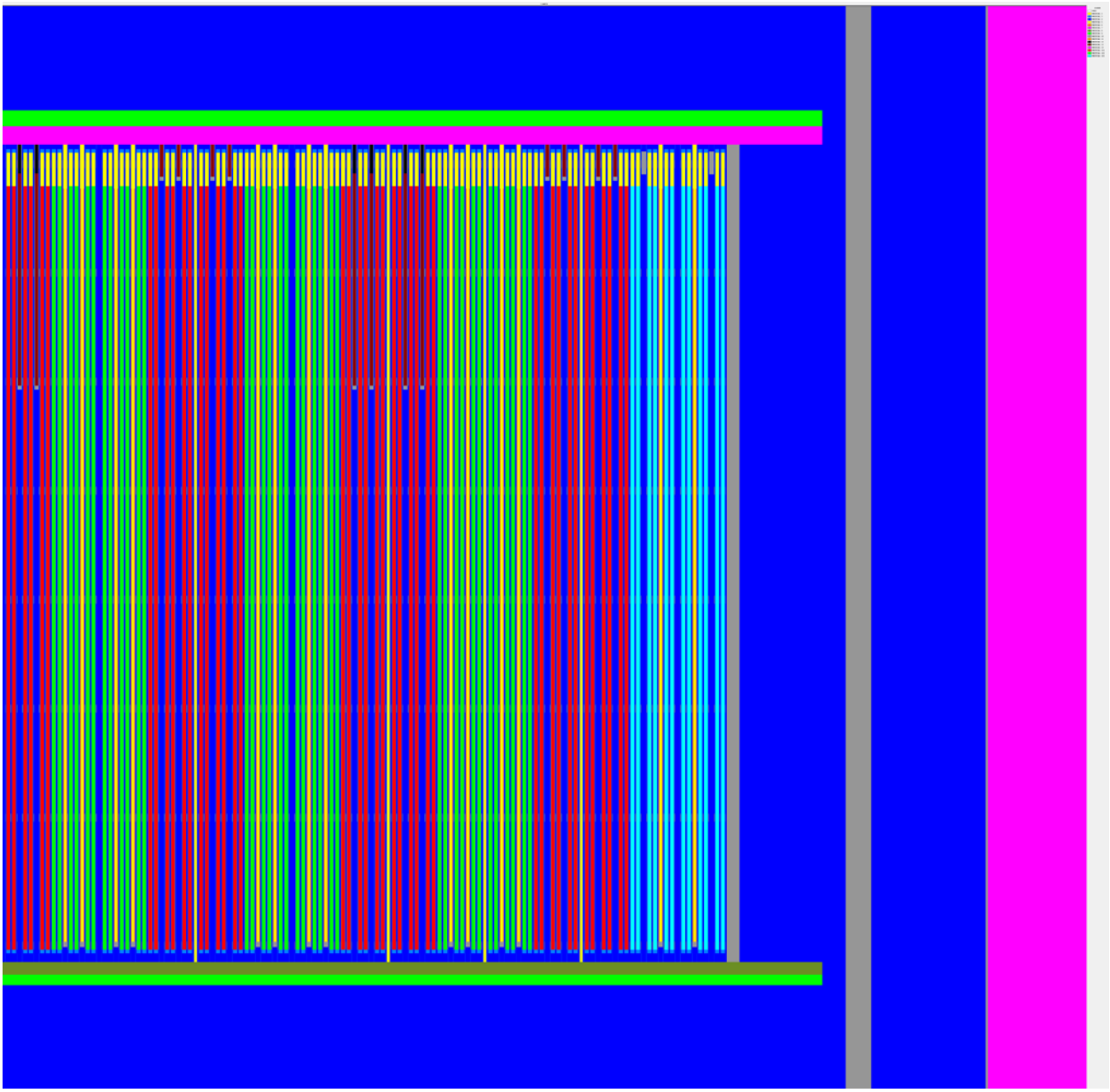


**Figure P5-3: Problem 5 Axial KENO-VI Geometry (not to proportion)**

### *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 the development version of SCALE 6.2 on cpile2.ornl.gov from location **/scale/scale_dev/staging-mpi**.

### *Mixing Table*

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

**Table P5-3: Reference Mixing Table**

| Material | Isotope ID | Atom Density (/barn-cm) |
|---|---|---|
| **2.1% 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 |
| **1300 ppm Moderator** | 1001 | 4.96224E-02 |
| | 5010 | 1.07070E-05 |
| | 5011 | 4.30971E-05 |
| | 8016 | 2.48112E-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 | 4.00685E-02 |
| | 5010 | 9.44445E-06 |
| | 5011 | 3.80151E-05 |
| | 6000 | 6.13703E-05 |
| | 8016 | 2.00342E-02 |
| | 14028 | 3.02547E-04 |
| | 14029 | 1.53696E-05 |
| | 14030 | 1.01436E-05 |
| | 15031 | 1.33861E-05 |
| | 24050 | 1.46288E-04 |
| | 24052 | 2.82102E-03 |
| | 24053 | 3.19881E-04 |
| | 24054 | 7.96251E-05 |
| | 25055 | 3.35423E-04 |
| | 26054 | 6.59376E-04 |
| | 26056 | 1.03508E-02 |
| | 26057 | 2.39045E-04 |
| | 26058 | 3.18125E-05 |
| | 28058 | 1.01525E-03 |
| | 28060 | 3.91071E-04 |
| | 28061 | 1.69996E-05 |
| | 28062 | 5.42021E-05 |
| | 28064 | 1.38037E-05 |
| **Bottom Nozzle** | 1001 | 3.57697E-02 |
| | 5010 | 9.21166E-06 |
| | 5011 | 3.70781E-05 |
| | 6000 | 8.96212E-05 |
| | 8016 | 1.78849E-02 |
| | 14028 | 4.41821E-04 |
| | 14029 | 2.24448E-05 |
| | 14030 | 1.48131E-05 |
| | 15031 | 1.95482E-05 |
| | 24050 | 2.13630E-04 |

| | | |
|---|---|---|
| | 24052 | 4.11963E-03 |
| | 24053 | 4.67133E-04 |
| | 24054 | 1.16279E-04 |
| | 25055 | 4.89830E-04 |
| | 26054 | 9.62909E-04 |
| | 26056 | 1.51156E-02 |
| | 26057 | 3.49086E-04 |
| | 26058 | 4.64569E-05 |
| | 28058 | 1.48260E-03 |
| | 28060 | 5.71094E-04 |
| | 28061 | 2.48251E-05 |
| | 28062 | 7.91532E-05 |
| | 28064 | 2.01580E-05 |
| **Core Plates** | 1001 | 2.48109E-02 |
| | 5010 | 4.84416E-06 |
| | 5011 | 1.94983E-05 |
| | 6000 | 1.60389E-04 |
| | 8016 | 1.24055E-02 |
| | 14028 | 7.90698E-04 |
| | 14029 | 4.01681E-05 |
| | 14030 | 2.65101E-05 |
| | 15031 | 3.49842E-05 |
| | 24050 | 3.82319E-04 |
| | 24052 | 7.37264E-03 |
| | 24053 | 8.35998E-04 |
| | 24054 | 2.08098E-04 |
| | 25055 | 8.76618E-04 |
| | 26054 | 1.72326E-03 |
| | 26056 | 2.70514E-02 |
| | 26057 | 6.24736E-04 |
| | 26058 | 8.31409E-05 |
| | 28058 | 2.65331E-03 |
| | 28060 | 1.02205E-03 |
| | 28061 | 4.44278E-05 |
| | 28062 | 1.41655E-04 |
| | 28064 | 3.60754E-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 |
| **B4C** | 5010 | 1.52689E-02 |
| | 5011 | 6.14591E-02 |
| | 6000 | 1.91820E-02 |
| **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 |
| **Carbon Steel** | 6000 | 3.93598E-03 |
| | 26054 | 4.89841E-03 |
| | 26056 | 7.68945E-02 |
| | 26057 | 1.77583E-03 |
| | 26058 | 2.36330E-04 |

## REFERENCE SOLUTION RESULTS

The eigenvalues calculated by CE KENO-VI for the reference cases are provided below. A series of eigenvalues were calculated at various rod positions and soluble boron concentrations, as indicated in the tables. These values are used to calculate the subsequent ZPPT reactivity coefficients.

The reference ZPPT solutions are calculated based on the following assumptions:

1. Core initial criticality is achieved by positioning of the main regulating control rod bank, Bank D, at a boron concentration of 1300 ppm.
2. The control Bank D worth is measured via soluble boron dilution. The reference worth is calculated by Bank D insertion at an average boron concentration over the dilution of 1200 ppm.
3. The remaining control bank reactivity worths are measured via rod swap against Bank D at the boron dilution endpoint of 1100 ppm. The reference bank worths are calculated at an average Bank D position, assumed here to be 110 steps withdrawn for all banks, for simplicity.
4. The Differential Boron Worth (DBW) is calculated over the range of Bank D measurements as an average of the worth with Bank D fully withdrawn and the worth of Bank D fully inserted.
5. The Isothermal Temperature Coefficient (ITC) is calculated over the range of 565K to 600K due to limited temperatures available on the continuous energy data libraries for KENO-VI.

**Table P5-4: Problem 5 Reference Solution Eigenvalue Results**

| | Bank Position | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Boron** | **A** | **B** | **C** | **D** | **SA** | **SB** | **SC** | **SD** | **Eigenvalue** |
| 1300 | - | - | - | 167 | - | - | - | - | **0.999399 ± 0.000073** |
| 1300 | - | - | - | - | - | - | - | - | **1.000492 ± 0.000097** |
| 1200 | - | - | - | - | - | - | - | - | **1.010512 ± 0.000080** |
| 1200 | - | - | - | 0 | - | - | - | - | **0.996781 ± 0.000084** |
| 1100 | - | - | - | 0 | - | - | - | - | **1.007124 ± 0.000078** |
| 1100 | - | - | - | 110 | - | - | - | - | **1.016612 ± 0.000078** |
| 1100 | - | - | 0 | 110 | - | - | - | - | **1.006396 ± 0.000078** |
| 1100 | - | 0 | - | 110 | - | - | - | - | **1.00727 ± 0.00010** |
| 1100 | 0 | - | - | 110 | - | - | - | - | **1.00782 ± 0.00011** |
| 1100 | - | - | - | 110 | - | - | - | 0 | **1.01219 ± 0.00010** |
| 1100 | - | - | - | 110 | - | - | 0 | - | **1.01207 ± 0.00012** |
| 1100 | - | - | - | 110 | - | 0 | - | - | **1.00588 ± 0.00011** |
| 1100 | - | - | - | 110 | 0 | - | - | - | **1.01228 ± 0.00010** |

*All cases at 565K and 0.743 g/cc moderator temperature and density

In addition to the items in the previous table, and additional case was run at the CE temperature of 600K and 0.661 g/cc, with Bank D fully inserted and a boron concentration of 1100 ppm. This case will be used to calculate the Isothermal Temperature Coefficient (ITC), though the temperature difference is likely much too great to compare to measured values. The eigenvalue for this case was **0.99904 ± 0.00011**.

Based on the eigenvalues above, the ZPPT control bank worths, differential boron worth, and isothermal temperature coefficient were calculated and provided in the table below, calculated by:

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

**Table P5-5: Problem 5 Reference Solution ZPPT Results**

| Zero Power Physics Test | CE KENO-VI Reference Value (pcm) |
|---|---|
| Initial Criticality† | **-60 ± 7** |
| Bank D Worth | **-1363 ± 12** |
| Bank C Worth | **-999 ± 11** |
| Bank B Worth | **-912 ± 13** |
| Bank A Worth | **-858 ± 13** |
| Bank SD Worth | **-439 ± 14** |
| Bank SC Worth | **-441 ± 14** |
| Bank SB Worth | **-1049 ± 13** |
| Bank SA Worth | **-421 ± 13** |
| Total Bank Worths | **-6483 ± 37** |
| DBW | **-10.1 ± 0.2 pcm/ppm** |
| ITC | **-12.8 ± 0.2 pcm/F** |

†Critical conditions are 1300 ppm and Bank D at 167 steps withdrawn

The individual pin powers are not calculated for Problem 5Summary results for 1D and 2D power shapes will be provided in a later revision, as new tools come available for these visualizations.

# 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) and AIC (1.6) absorbers in the assembly guide tubes.

Figure M1-1 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 2.1% enrichment with center RCCA, and Region 2 is the 2.6% enriched region with the 20 Pyrex rods. This problem is ideally run in quarter or octant symmetry.

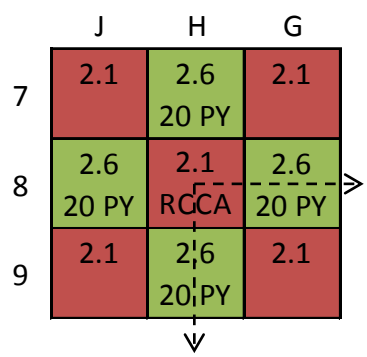



**Figure M1-1: Problem 4-2D Assembly, Poison, and Control Layout**

**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
- The 20 Pyrex pattern (Section 1.5) does 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 #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.

## 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). Results for SCALE CE ENDF/B-VI.8 cross sections are included in Appendix D.

### *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 (www.wikipedia.com). 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, 1e9 particles are used, skipping 200 generations. This resulted in an eigenvalue uncertainty of less than **3 pcm**. The maximum estimated uncertainty in pin powers is provided below as a function of pin power level.

**Table M1-3: Problem 4-2D Maximum Pin Power Uncertainty vs. Pin Power**

| Pin Power Range | Maximum Estimated Fractional Uncertainty | |
|---|---|---|
| | Uncontrolled | Controlled |
| 0.0 < 0.5 | -- | 0.13% |
| 0.5 – 1.0 | 0.099% | 0.12% |
| > 1.0 | 0.090% | 0.08% |

***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.

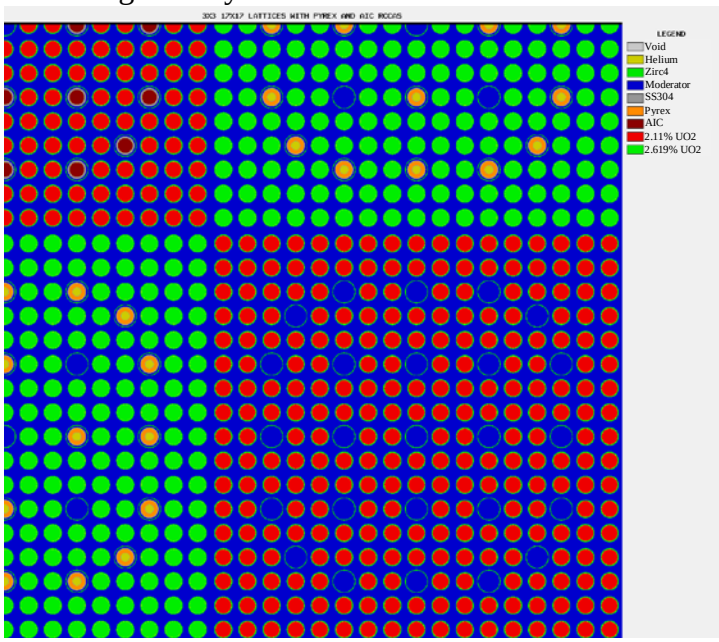



**Figure M1-2: Problem 4-2D Radial Geometry**

### *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 the development version of SCALE 6.2 on cpile2.ornl.gov from location **/scale/scale_dev/staging-mpi**. These calculations ran on ~64 processors for ~12 hours.

### *Mixing Table*

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

**Table M1-4: 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 |
| **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 |
| **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 |

## REFERENCE SOLUTION RESULTS

Both controlled and uncontrolled cases were executed 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 D. The control rod reactivity worth calculation is done as:

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

Also, note that the reference KENO-VI results are calculated in 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 M1-5: Problem 4-2D Reference Solution Results**

| Case | Results |
|---|---|
| Uncontrolled | **1.010925 ± 0.000023** |
| Controlled | **0.984155 ± 0.000025** |
| Rod Worth | **-2691 ± 3** |

**Table M1-6: Problem 4-2D Reference Solution Power Statistics**

| Powers | Quantity | Uncontrolled | Controlled |
|---|---|---|---|
| Assembly Powers | Maximum | 1.0777 | 1.1808 |
| | Average Uncertainty | 0.065% | 0.067% |
| | Maximum Uncertainty | 0.069% | 0.091% |
| Pin Powers | Maximum | 1.1921 | 1.3558 |
| | Average Uncertainty | 0.065% | 0.067% |
| | Maximum Uncertainty | 0.099% | 0.130% |

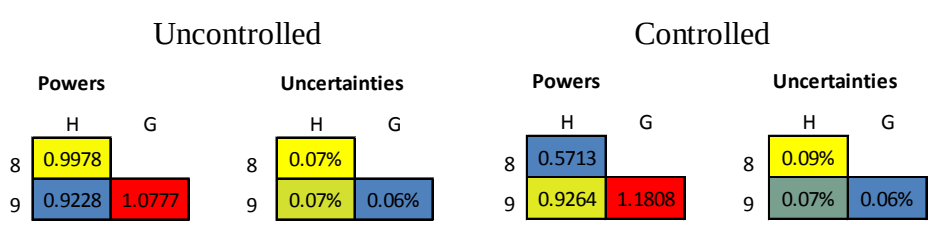



**Figure M1-3: Problem 4-2D Assembly Power Distributions**

| | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.073 | 1.052 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.071 | 1.048 | 1.049 | | | | | | | | | | | | | | | | | | | | | | | | |
| | 1.068 | 1.068 | | | | | | | | | | | | | | | | | | | | | | | | |
| 1.062 | 1.040 | 1.040 | 1.066 | 1.052 | | | | | | | | | | | | | | | | | | | | | | |
| 1.049 | 1.029 | 1.030 | 1.059 | 1.059 | | | | | | | | | | | | | | | | | | | | | | |
| | 1.029 | 1.030 | | 1.035 | 1.016 | 0.975 | | | | | | | | | | | | | | | | | | | | |
| 0.990 | 0.973 | 0.974 | 0.992 | 0.972 | 0.958 | 0.942 | 0.930 | | | | | | | | | | | | | | | | | | | |
| 0.921 | 0.918 | 0.919 | 0.923 | 0.919 | 0.918 | 0.917 | 0.915 | 0.916 | | | | | | | | | | | | | | | | | | |
| 1.009 | 1.013 | 1.014 | 1.014 | 1.023 | 1.032 | 1.045 | 1.061 | 1.085 | 0.919 | | | | | | | | | | | | | | | | | |
| 0.894 | 0.922 | 0.925 | 0.899 | 0.934 | 0.961 | 0.992 | 1.023 | 1.065 | 0.922 | 0.939 | | | | | | | | | | | | | | | | |
| | 0.845 | 0.849 | | 0.842 | 0.869 | 0.936 | 0.994 | 1.052 | 0.925 | 0.956 | 0.992 | | | | | | | | | | | | | | | |
| 0.826 | 0.865 | 0.874 | 0.844 | 0.826 | | 0.873 | 0.967 | 1.043 | 0.930 | 0.973 | 1.037 | | | | | | | | | | | | | | | |
| 0.830 | 0.874 | 0.913 | 0.931 | 0.888 | 0.828 | 0.849 | 0.942 | 1.036 | 0.935 | 0.991 | 1.059 | 1.089 | 1.084 | | | | | | | | | | | | | |
| | 0.859 | 0.943 | | 0.933 | 0.847 | | 0.909 | 1.029 | 0.939 | 1.014 | | 1.091 | 1.103 | | | | | | | | | | | | | |
| 0.868 | 0.900 | 0.928 | 0.945 | 0.915 | 0.880 | 0.857 | 0.938 | 1.032 | 0.938 | 0.998 | 1.059 | 1.065 | 1.079 | 1.113 | 1.097 | | | | | | | | | | | |
| 0.953 | 0.930 | 0.900 | 0.861 | 0.877 | 0.870 | 0.854 | 0.937 | 1.033 | 0.940 | 1.000 | 1.061 | 1.066 | 1.082 | 1.117 | 1.103 | 1.110 | | | | | | | | | | |
| | 0.952 | 0.868 | | 0.833 | 0.832 | | 0.908 | 1.029 | 0.944 | 1.020 | | 1.091 | 1.109 | | 1.130 | 1.137 | | | | | | | | | | |
| 0.951 | 0.928 | 0.899 | 0.859 | 0.875 | 0.869 | 0.854 | 0.938 | 1.035 | 0.945 | 1.005 | 1.068 | 1.072 | 1.091 | 1.127 | 1.113 | 1.119 | 1.148 | 1.131 | | | | | | | | |
| 0.864 | 0.895 | 0.923 | 0.941 | 0.913 | 0.878 | 0.857 | 0.939 | 1.037 | 0.945 | 1.008 | 1.071 | 1.079 | 1.096 | 1.131 | 1.117 | 1.123 | 1.154 | 1.137 | 1.142 | | | | | | | |
| | 0.852 | 0.936 | | 0.928 | 0.845 | | 0.911 | 1.035 | 0.949 | 1.029 | | 1.113 | 1.128 | | 1.143 | 1.151 | | 1.164 | 1.170 | | | | | | | |
| 0.817 | 0.861 | 0.900 | 0.921 | 0.880 | 0.825 | 0.847 | 0.946 | 1.043 | 0.949 | 1.010 | 1.084 | 1.118 | 1.120 | 1.143 | 1.125 | 1.129 | 1.158 | 1.142 | 1.149 | 1.183 | 1.176 | | | | | |
| 0.807 | 0.844 | 0.855 | 0.828 | 0.814 | | 0.869 | 0.970 | 1.054 | 0.947 | 0.999 | 1.071 | | 1.137 | 1.145 | 1.123 | 1.129 | 1.159 | 1.141 | 1.149 | 1.186 | 1.192 | | | | | |
| | 0.810 | 0.815 | | 0.818 | 0.850 | 0.924 | 0.994 | 1.064 | 0.947 | 0.988 | 1.036 | 1.093 | 1.125 | | 1.140 | 1.146 | | 1.159 | 1.166 | | 1.180 | 1.166 | 1.127 | | | |
| 0.830 | 0.858 | 0.863 | 0.842 | 0.885 | 0.920 | 0.965 | 1.013 | 1.073 | 0.950 | 0.984 | 1.016 | 1.050 | 1.079 | 1.115 | 1.106 | 1.112 | 1.140 | 1.126 | 1.132 | 1.156 | 1.134 | 1.119 | 1.105 | 1.097 | | |
| 0.891 | 0.897 | 0.903 | 0.906 | 0.927 | 0.956 | 0.990 | 1.032 | 1.087 | 0.957 | 0.987 | 1.015 | 1.041 | 1.063 | 1.084 | 1.091 | 1.100 | 1.111 | 1.112 | 1.117 | 1.123 | 1.118 | 1.110 | 1.103 | 1.100 | 1.104 | |

**Figure M1-4: Problem 4-2D Uncontrolled Pin Power Distribution**

| | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0.552 | 0.535 | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0.486 | 0.503 | 0.491 | | | | | | | | | | | | | | | | | | | | | | | | |
| | 0.463 | 0.459 | | | | | | | | | | | | | | | | | | | | | | | | |
| 0.463 | 0.490 | 0.488 | 0.458 | 0.475 | | | | | | | | | | | | | | | | | | | | | | |
| 0.471 | 0.503 | 0.502 | 0.466 | 0.471 | | | | | | | | | | | | | | | | | | | | | | |
| | 0.504 | 0.505 | | 0.518 | 0.563 | 0.638 | | | | | | | | | | | | | | | | | | | | |
| 0.555 | 0.580 | 0.584 | 0.570 | 0.613 | 0.655 | 0.702 | 0.744 | | | | | | | | | | | | | | | | | | | |
| 0.633 | 0.639 | 0.644 | 0.651 | 0.676 | 0.705 | 0.741 | 0.775 | 0.808 | | | | | | | | | | | | | | | | | | |
| 0.779 | 0.786 | 0.792 | 0.801 | 0.827 | 0.859 | 0.899 | 0.942 | 0.991 | 0.863 | | | | | | | | | | | | | | | | | |
| 0.742 | 0.769 | 0.775 | 0.759 | 0.803 | 0.844 | 0.891 | 0.941 | 1.000 | 0.885 | 0.916 | | | | | | | | | | | | | | | | |
| | 0.745 | 0.752 | | 0.760 | 0.794 | 0.869 | 0.940 | 1.013 | 0.906 | 0.949 | 0.997 | | | | | | | | | | | | | | | |
| 0.760 | 0.795 | 0.808 | 0.786 | 0.773 | | 0.834 | 0.937 | 1.023 | 0.925 | 0.981 | 1.056 | | | | | | | | | | | | | | | |
| 0.785 | 0.827 | 0.866 | 0.890 | 0.853 | 0.803 | 0.826 | 0.930 | 1.032 | 0.944 | 1.011 | 1.091 | 1.131 | 1.138 | | | | | | | | | | | | | |
| | 0.833 | 0.916 | | 0.915 | 0.836 | | 0.912 | 1.043 | 0.962 | 1.046 | | 1.145 | 1.167 | | | | | | | | | | | | | |
| 0.860 | 0.891 | 0.918 | 0.938 | 0.912 | 0.882 | 0.866 | 0.955 | 1.058 | 0.971 | 1.042 | 1.116 | 1.129 | 1.153 | 1.197 | 1.188 | | | | | | | | | | | |
| 0.958 | 0.936 | 0.906 | 0.868 | 0.888 | 0.885 | 0.874 | 0.966 | 1.072 | 0.984 | 1.054 | 1.126 | 1.138 | 1.165 | 1.208 | 1.199 | 1.214 | | | | | | | | | | |
| | 0.969 | 0.885 | | 0.855 | 0.859 | | 0.948 | 1.081 | 0.998 | 1.084 | | 1.174 | 1.202 | | 1.238 | 1.251 | | | | | | | | | | |
| 0.980 | 0.957 | 0.929 | 0.891 | 0.910 | 0.908 | 0.895 | 0.989 | 1.097 | 1.006 | 1.078 | 1.150 | 1.163 | 1.188 | 1.232 | 1.222 | 1.239 | 1.276 | 1.261 | | | | | | | | |
| 0.900 | 0.933 | 0.963 | 0.984 | 0.957 | 0.924 | 0.905 | 0.999 | 1.108 | 1.014 | 1.087 | 1.163 | 1.175 | 1.201 | 1.245 | 1.234 | 1.248 | 1.287 | 1.271 | 1.280 | | | | | | | |
| | 0.896 | 0.985 | | 0.979 | 0.896 | | 0.977 | 1.114 | 1.027 | 1.116 | | 1.217 | 1.241 | | 1.270 | 1.282 | | 1.305 | 1.317 | | | | | | | |
| 0.866 | 0.911 | 0.954 | 0.976 | 0.935 | 0.881 | 0.907 | 1.020 | 1.129 | 1.029 | 1.101 | 1.186 | 1.230 | 1.235 | 1.267 | 1.250 | 1.263 | 1.300 | 1.283 | 1.296 | 1.339 | 1.333 | | | | | |
| 0.857 | 0.898 | 0.911 | 0.883 | 0.870 | | 0.936 | 1.049 | 1.143 | 1.033 | 1.093 | 1.176 | | 1.259 | 1.271 | 1.254 | 1.265 | 1.303 | 1.285 | 1.300 | 1.343 | 1.356 | | | | | |
| | 0.867 | 0.872 | | 0.879 | 0.917 | 1.000 | 1.077 | 1.158 | 1.036 | 1.086 | 1.141 | 1.208 | 1.248 | | 1.274 | 1.286 | | 1.311 | 1.320 | | 1.342 | 1.327 | 1.286 | | | |
| 0.889 | 0.921 | 0.926 | 0.906 | 0.954 | 0.995 | 1.047 | 1.101 | 1.172 | 1.040 | 1.080 | 1.122 | 1.163 | 1.200 | 1.244 | 1.237 | 1.251 | 1.286 | 1.274 | 1.283 | 1.313 | 1.290 | 1.277 | 1.260 | 1.253 | | |
| 0.957 | 0.964 | 0.970 | 0.976 | 1.001 | 1.034 | 1.074 | 1.123 | 1.188 | 1.049 | 1.087 | 1.121 | 1.154 | 1.184 | 1.210 | 1.223 | 1.237 | 1.252 | 1.258 | 1.267 | 1.277 | 1.272 | 1.266 | 1.258 | 1.256 | 1.264 | |

**Figure M1-5: Problem 4-2D Controlled Pin Power Distribution**

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0.09% | 0.09% | | | | | | | | | | | | | | | | | | | | | | | | |
| 0.09% | 0.06% | 0.09% | | | | | | | | | | | | | | | | | | | | | | | |
| | 0.06% | 0.06% | | | | | | | | | | | | | | | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | | | | | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.06% | | | | | | | | | | | | | | | | | | | | | |
| | 0.06% | 0.06% | | 0.06% | 0.06% | 0.09% | | | | | | | | | | | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | | | | | | | |
| | 0.06% | 0.07% | | 0.07% | 0.06% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | | | | | | |
| 0.10% | 0.07% | 0.06% | 0.07% | 0.07% | | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | | | | | | | | | | | | | | |
| 0.10% | 0.07% | 0.06% | 0.06% | 0.07% | 0.07% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | | | | |
| | 0.06% | 0.06% | | 0.06% | 0.07% | | 0.06% | 0.06% | 0.06% | 0.06% | | 0.06% | 0.06% | | | | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.06% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.07% | 0.07% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | |
| | 0.06% | 0.07% | | 0.07% | 0.07% | | 0.06% | 0.06% | 0.06% | 0.06% | | 0.06% | 0.06% | | 0.06% | 0.06% | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.07% | 0.07% | 0.06% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% | | | | | | | |
| 0.10% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% | | | | | |
| | 0.07% | 0.06% | | 0.06% | 0.07% | | 0.06% | 0.06% | 0.06% | 0.06% | | 0.06% | 0.06% | | 0.06% | 0.06% | | 0.06% | 0.06% | | | | | | |
| 0.10% | 0.07% | 0.06% | 0.06% | 0.06% | 0.07% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% | | | |
| 0.10% | 0.07% | 0.07% | 0.07% | 0.07% | | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | | | |
| | 0.07% | 0.07% | | 0.07% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | | 0.06% | 0.06% | | 0.06% | 0.06% | | 0.06% | 0.06% | 0.08% | |
| 0.10% | 0.07% | 0.06% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% |
| 0.09% | 0.06% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.09% |

**Figure M1-6: Problem 4-2D Uncontrolled Pin Power Estimated Uncertainties**

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | | | | | | |
| 0.12% | 0.12% | | | | | | | | | | | | | | | | | | | | | | | | |
| 0.12% | 0.09% | 0.13% | | | | | | | | | | | | | | | | | | | | | | | |
| | 0.09% | 0.09% | | | | | | | | | | | | | | | | | | | | | | | |
| 0.13% | 0.09% | 0.09% | 0.09% | 0.13% | | | | | | | | | | | | | | | | | | | | | |
| 0.13% | 0.09% | 0.09% | 0.09% | 0.09% | | | | | | | | | | | | | | | | | | | | | |
| | 0.09% | 0.09% | | 0.09% | 0.08% | 0.11% | | | | | | | | | | | | | | | | | | | |
| 0.12% | 0.08% | 0.08% | 0.09% | 0.08% | 0.08% | 0.07% | 0.11% | | | | | | | | | | | | | | | | | | |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.07% | 0.07% | 0.10% | | | | | | | | | | | | | | | | | |
| 0.10% | 0.07% | 0.07% | 0.07% | 0.07% | 0.07% | 0.06% | 0.06% | 0.06% | 0.10% | | | | | | | | | | | | | | | | |
| 0.10% | 0.07% | 0.07% | 0.07% | 0.07% | 0.07% | 0.07% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | | | | | | | |
| | 0.07% | 0.07% | | 0.07% | 0.07% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.09% | | | | | | | | | | | | | | |
| 0.10% | 0.07% | 0.07% | 0.07% | 0.07% | | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | | | | | | | | | | | | | | |
| 0.10% | 0.07% | 0.07% | 0.07% | 0.07% | 0.07% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% | | | | | | | | | | | | |
| | 0.07% | 0.06% | | 0.06% | 0.07% | | 0.06% | 0.06% | 0.06% | 0.06% | | 0.06% | 0.06% | | | | | | | | | | | | |
| 0.10% | 0.07% | 0.06% | 0.06% | 0.06% | 0.07% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% | | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.06% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% | | | | | | | | | |
| | 0.06% | 0.06% | | 0.07% | 0.07% | | 0.06% | 0.06% | 0.06% | 0.06% | | 0.06% | 0.06% | | 0.06% | 0.06% | | | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% | | | | | | | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% | | | | | | |
| | 0.07% | 0.06% | | 0.06% | 0.07% | | 0.06% | 0.06% | 0.06% | 0.06% | | 0.06% | 0.06% | | 0.06% | 0.06% | | 0.06% | 0.06% | | | | | | |
| 0.10% | 0.06% | 0.06% | 0.06% | 0.06% | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% | | | | |
| 0.10% | 0.06% | 0.07% | 0.07% | 0.07% | | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | | | | |
| | 0.07% | 0.07% | | 0.07% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | | 0.06% | 0.06% | | 0.06% | 0.06% | | 0.06% | 0.06% | 0.08% | | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% | |
| 0.09% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.06% | 0.08% |

**Figure M1-7: Problem 4-2D Controlled Pin Power Estimated Uncertainties**

## 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 2.1% enrichment, and Region 2 is the 3.1% enriched region with the indicated number of Pyrex rods. This problem must be run in full symmetry.

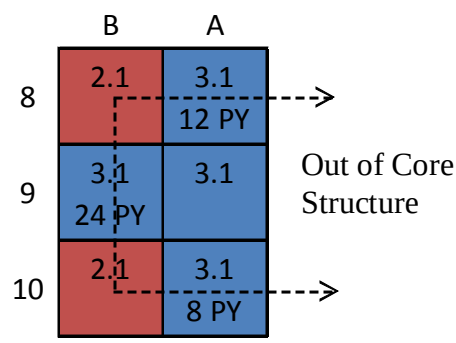



**Figure M2-1: Problem REF1-2D Assembly and Poison Configuration**

**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 (www.wikipedia.com). 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 WB1N. 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.

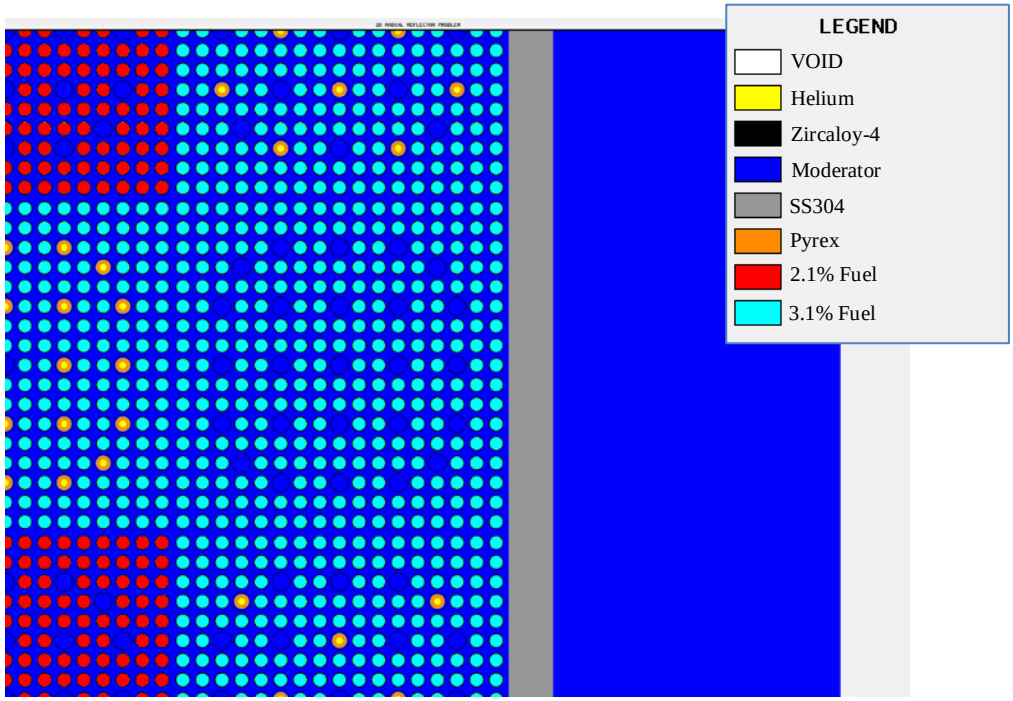



**Figure M2-2: Problem REF1-2D Radial Geometry**

### *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 |
| **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 E.

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**

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1.207 | 1.203 | | 1.183 | 1.170 | | 1.089 | 1.004 | 1.265 | 1.214 | | 1.090 | 0.958 | | 0.880 | 0.924 | | 0.844 | 0.730 | | 0.632 | 0.642 | | 0.537 | 0.442 |
| 1.205 | 1.180 | 1.176 | 1.196 | 1.160 | 1.143 | 1.135 | 1.067 | 1.000 | 1.258 | 1.176 | 1.139 | 1.063 | 0.992 | 0.920 | 0.912 | 0.903 | 0.885 | 0.822 | 0.752 | 0.685 | 0.658 | 0.628 | 0.590 | 0.519 | 0.438 |
| 1.205 | 1.180 | 1.176 | 1.196 | 1.162 | 1.146 | 1.136 | 1.066 | 0.994 | 1.241 | 1.126 | 1.036 | 1.032 | 1.026 | 1.012 | 0.948 | 0.880 | 0.809 | 0.795 | 0.777 | 0.750 | 0.687 | 0.616 | 0.541 | 0.494 | 0.430 |
| | 1.198 | 1.197 | | 1.190 | 1.173 | | 1.084 | 0.994 | 1.230 | 1.083 | | 1.006 | 1.060 | | 0.982 | 0.858 | | 0.770 | 0.800 | | 0.715 | 0.608 | | 0.473 | 0.427 |
| 1.192 | 1.167 | 1.167 | 1.192 | 1.171 | 1.173 | 1.138 | 1.060 | 0.988 | 1.238 | 1.129 | 1.055 | 1.087 | 1.056 | 1.031 | 0.963 | 0.893 | 0.822 | 0.806 | 0.789 | 0.766 | 0.710 | 0.654 | 0.555 | 0.500 | 0.435 |
| 1.178 | 1.153 | 1.154 | 1.183 | 1.179 | | 1.117 | 1.040 | 0.981 | 1.244 | 1.166 | 1.150 | | 1.060 | 0.951 | 0.939 | 0.928 | 0.910 | 0.844 | 0.775 | 0.707 | 0.706 | | 0.608 | 0.523 | 0.445 |
| | 1.151 | 1.150 | | 1.148 | 1.121 | 1.066 | 1.017 | 0.973 | 1.244 | 1.174 | 1.139 | 1.120 | 0.998 | | 0.914 | 0.964 | | 0.883 | 0.762 | | 0.664 | 0.671 | 0.604 | 0.533 | 0.451 |
| 1.102 | 1.080 | 1.083 | 1.098 | 1.071 | 1.047 | 1.023 | 0.996 | 0.963 | 1.243 | 1.178 | 1.135 | 1.096 | 1.031 | 0.957 | 0.961 | 0.964 | 0.956 | 0.880 | 0.799 | 0.716 | 0.693 | 0.661 | 0.606 | 0.539 | 0.458 |
| 1.014 | 1.010 | 1.009 | 1.011 | 1.001 | 0.991 | 0.981 | 0.963 | 0.944 | 1.240 | 1.187 | 1.151 | 1.116 | 1.077 | 1.036 | 1.012 | 0.983 | 0.953 | 0.898 | 0.841 | 0.777 | 0.731 | 0.678 | 0.620 | 0.551 | 0.468 |
| 1.250 | 1.253 | 1.252 | 1.246 | 1.250 | 1.252 | 1.255 | 1.251 | 1.249 | 1.221 | 1.184 | 1.160 | 1.139 | 1.111 | 1.087 | 1.052 | 1.014 | 0.978 | 0.925 | 0.872 | 0.821 | 0.761 | 0.699 | 0.634 | 0.561 | 0.475 |
| 1.089 | 1.122 | 1.122 | 1.090 | 1.123 | 1.144 | 1.168 | 1.188 | 1.203 | 1.197 | 1.176 | 1.167 | 1.163 | 1.154 | 1.153 | 1.090 | 1.051 | 1.029 | 0.959 | 0.906 | 0.872 | 0.794 | 0.722 | 0.645 | 0.567 | 0.479 |
| | 1.015 | 1.013 | | 1.000 | 1.029 | 1.095 | 1.141 | 1.174 | 1.187 | 1.187 | 1.203 | 1.233 | 1.228 | | 1.148 | 1.102 | | 1.008 | 0.954 | | 0.847 | 0.770 | 0.671 | 0.580 | 0.486 |
| 0.980 | 1.017 | 1.011 | 0.960 | 0.953 | | 1.014 | 1.105 | 1.158 | 1.188 | 1.202 | 1.259 | | 1.254 | 1.214 | 1.137 | 1.093 | 1.074 | 0.998 | 0.946 | 0.921 | 0.865 | | 0.710 | 0.597 | 0.495 |
| 0.970 | 1.005 | 1.000 | 0.952 | 0.968 | 0.946 | 0.980 | 1.073 | 1.146 | 1.190 | 1.224 | 1.282 | 1.286 | 1.237 | 1.222 | 1.148 | 1.102 | 1.085 | 1.007 | 0.958 | 0.930 | 0.857 | 0.807 | 0.726 | 0.613 | 0.502 |
| | 0.972 | 0.967 | | 0.949 | 0.949 | | 1.033 | 1.135 | 1.194 | 1.257 | | 1.282 | 1.256 | | 1.185 | 1.140 | | 1.043 | 0.988 | | 0.873 | 0.808 | | 0.634 | 0.511 |
| 1.012 | 1.032 | 1.015 | 0.965 | 0.995 | 0.999 | 0.985 | 1.065 | 1.140 | 1.194 | 1.229 | 1.277 | 1.244 | 1.222 | 1.225 | 1.158 | 1.116 | 1.098 | 1.020 | 0.966 | 0.935 | 0.851 | 0.782 | 0.726 | 0.623 | 0.511 |
| 1.122 | 1.088 | 1.032 | 0.972 | 1.001 | 1.005 | 0.987 | 1.066 | 1.141 | 1.192 | 1.230 | 1.279 | 1.241 | 1.223 | 1.228 | 1.160 | 1.119 | 1.102 | 1.024 | 0.971 | 0.937 | 0.852 | 0.785 | 0.730 | 0.623 | 0.513 |
| | 1.125 | 1.016 | | 0.968 | 0.971 | | 1.037 | 1.139 | 1.200 | 1.262 | | 1.276 | 1.258 | | 1.195 | 1.149 | | 1.054 | 1.001 | | 0.877 | 0.807 | | 0.641 | 0.517 |
| 1.125 | 1.091 | 1.037 | 0.977 | 1.003 | 1.009 | 0.993 | 1.070 | 1.147 | 1.198 | 1.237 | 1.283 | 1.247 | 1.229 | 1.233 | 1.167 | 1.125 | 1.107 | 1.030 | 0.975 | 0.942 | 0.858 | 0.789 | 0.733 | 0.626 | 0.516 |
| 1.020 | 1.041 | 1.020 | 0.973 | 1.002 | 1.008 | 0.994 | 1.072 | 1.149 | 1.201 | 1.238 | 1.286 | 1.254 | 1.231 | 1.238 | 1.168 | 1.127 | 1.109 | 1.031 | 0.978 | 0.944 | 0.859 | 0.793 | 0.735 | 0.628 | 0.517 |
| | 0.983 | 0.979 | | 0.961 | 0.961 | | 1.047 | 1.151 | 1.208 | 1.273 | | 1.302 | 1.276 | | 1.200 | 1.158 | | 1.061 | 1.003 | | 0.889 | 0.819 | | 0.644 | 0.518 |
| 0.985 | 1.019 | 1.016 | 0.967 | 0.983 | 0.962 | 0.994 | 1.091 | 1.166 | 1.212 | 1.245 | 1.307 | 1.310 | 1.261 | 1.249 | 1.171 | 1.127 | 1.109 | 1.031 | 0.979 | 0.951 | 0.876 | 0.826 | 0.741 | 0.626 | 0.513 |
| 0.996 | 1.037 | 1.031 | 0.978 | 0.970 | | 1.034 | 1.127 | 1.181 | 1.215 | 1.229 | 1.285 | | 1.288 | 1.247 | 1.171 | 1.122 | 1.104 | 1.025 | 0.974 | 0.949 | 0.891 | | 0.730 | 0.614 | 0.508 |
| | 1.037 | 1.035 | | 1.020 | 1.053 | 1.120 | 1.169 | 1.203 | 1.220 | 1.217 | 1.237 | 1.269 | 1.265 | | 1.188 | 1.141 | | 1.044 | 0.988 | | 0.877 | 0.795 | 0.695 | 0.601 | 0.501 |
| 1.120 | 1.152 | 1.150 | 1.117 | 1.154 | 1.178 | 1.202 | 1.221 | 1.235 | 1.230 | 1.215 | 1.206 | 1.205 | 1.198 | 1.200 | 1.138 | 1.098 | 1.075 | 1.003 | 0.949 | 0.911 | 0.829 | 0.752 | 0.673 | 0.589 | 0.496 |
| 1.284 | 1.289 | 1.287 | 1.284 | 1.288 | 1.290 | 1.292 | 1.292 | 1.288 | 1.258 | 1.226 | 1.202 | 1.186 | 1.169 | 1.151 | 1.114 | 1.073 | 1.036 | 0.980 | 0.927 | 0.874 | 0.807 | 0.735 | 0.664 | 0.586 | 0.495 |
| 1.044 | 1.041 | 1.042 | 1.042 | 1.035 | 1.025 | 1.014 | 0.999 | 0.978 | 1.286 | 1.228 | 1.192 | 1.167 | 1.154 | 1.136 | 1.100 | 1.065 | 1.025 | 0.970 | 0.918 | 0.862 | 0.792 | 0.721 | 0.652 | 0.578 | 0.489 |
| 1.139 | 1.119 | 1.119 | 1.134 | 1.109 | 1.086 | 1.060 | 1.032 | 0.998 | 1.289 | 1.217 | 1.170 | 1.140 | 1.139 | 1.155 | 1.105 | 1.067 | 1.045 | 0.973 | 0.918 | 0.875 | 0.785 | 0.699 | 0.632 | 0.564 | 0.481 |
| | 1.192 | 1.191 | | 1.191 | 1.163 | 1.110 | 1.062 | 1.016 | 1.299 | 1.214 | 1.141 | 1.076 | 1.138 | | 1.129 | 1.087 | | 0.991 | 0.936 | | 0.780 | 0.658 | 0.610 | 0.555 | 0.476 |
| 1.226 | 1.197 | 1.198 | 1.230 | 1.227 | | 1.164 | 1.090 | 1.032 | 1.314 | 1.219 | 1.114 | | 1.067 | 1.134 | 1.079 | 1.033 | 1.003 | 0.940 | 0.896 | 0.857 | 0.734 | | 0.587 | 0.551 | 0.476 |
| 1.239 | 1.212 | 1.212 | 1.238 | 1.222 | 1.226 | 1.192 | 1.111 | 1.047 | 1.335 | 1.260 | 1.213 | 1.104 | 1.116 | 1.134 | 1.061 | 0.978 | 0.897 | 0.884 | 0.873 | 0.851 | 0.758 | 0.666 | 0.640 | 0.569 | 0.480 |
| | 1.248 | 1.248 | | 1.243 | 1.227 | | 1.142 | 1.060 | 1.356 | 1.315 | | 1.209 | 1.171 | | 1.064 | 0.930 | | 0.836 | 0.873 | | 0.790 | 0.725 | | 0.596 | 0.487 |
| 1.255 | 1.228 | 1.225 | 1.247 | 1.214 | 1.198 | 1.195 | 1.128 | 1.062 | 1.359 | 1.299 | 1.282 | 1.194 | 1.132 | 1.101 | 1.027 | 0.950 | 0.872 | 0.859 | 0.842 | 0.820 | 0.758 | 0.712 | 0.676 | 0.586 | 0.488 |
| 1.256 | 1.229 | 1.228 | 1.248 | 1.213 | 1.198 | 1.195 | 1.130 | 1.066 | 1.363 | 1.304 | 1.285 | 1.184 | 1.088 | 0.999 | 0.985 | 0.972 | 0.951 | 0.883 | 0.813 | 0.743 | 0.724 | 0.704 | 0.675 | 0.588 | 0.489 |
| | 1.258 | 1.253 | | 1.239 | 1.223 | | 1.151 | 1.071 | 1.370 | 1.336 | | 1.203 | 1.049 | | 0.945 | 0.992 | | 0.907 | 0.786 | | 0.692 | 0.712 | | 0.602 | 0.491 |

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

| | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.11% | 0.12% | | 0.11% | 0.11% | | 0.12% | 0.12% | 0.11% | 0.11% | | 0.12% | 0.13% | | 0.13% | 0.13% | | 0.13% | 0.15% | | 0.15% | 0.15% | | 0.17% | 0.18% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.11% | 0.11% | 0.11% | 0.12% | 0.12% | 0.12% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | 0.10% | 0.11% | 0.11% | 0.12% | 0.12% | 0.13% |
| | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.08% | 0.09% | 0.08% | 0.08% | | 0.09% | 0.08% | | 0.09% | 0.09% | | 0.10% | 0.10% | | 0.10% | 0.11% | | 0.12% | 0.13% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | 0.10% | 0.10% | 0.11% | 0.12% | 0.12% | 0.13% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | | 0.11% | 0.12% | 0.13% |
| | 0.08% | 0.08% | | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | | 0.09% | 0.09% | | 0.09% | 0.10% | | 0.11% | 0.11% | 0.11% | 0.12% | 0.12% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.11% | 0.11% | 0.11% | 0.12% | 0.12% |
| 0.12% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | 0.11% | 0.11% | 0.11% | 0.12% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | 0.11% | 0.11% | 0.12% |
| 0.12% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | 0.11% | 0.12% |
| | 0.08% | 0.09% | | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.09% | 0.09% | | 0.10% | 0.10% | 0.11% | 0.12% | 0.12% |
| 0.12% | 0.09% | 0.09% | 0.09% | 0.09% | | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | | 0.10% | 0.11% | 0.12% |
| 0.13% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | 0.11% | 0.12% |
| | 0.09% | 0.09% | | 0.09% | 0.09% | | 0.09% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.09% | 0.09% | | 0.09% | 0.10% | | 0.11% | 0.12% |
| 0.12% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.11% | 0.12% |
| 0.12% | 0.08% | 0.09% | 0.08% | 0.09% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.11% | 0.11% | 0.12% |
| | 0.08% | 0.09% | | 0.09% | 0.09% | | 0.08% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.09% | 0.09% | | 0.09% | 0.10% | | 0.11% | 0.12% |
| 0.12% | 0.08% | 0.09% | 0.09% | 0.09% | 0.08% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | 0.11% | 0.12% |
| 0.12% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | 0.11% | 0.12% |
| | 0.09% | 0.09% | | 0.09% | 0.09% | | 0.09% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.09% | 0.09% | | 0.09% | 0.10% | | 0.11% | 0.12% |
| 0.12% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.11% | 0.12% |
| 0.12% | 0.08% | 0.09% | 0.09% | 0.09% | | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | | 0.10% | 0.11% | 0.12% |
| | 0.09% | 0.08% | | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.09% | 0.09% | | 0.09% | 0.10% | 0.10% | 0.11% | 0.12% |
| 0.12% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.10% | 0.10% | 0.11% | 0.11% | 0.12% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.08% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.11% | 0.11% | 0.12% |
| 0.12% | 0.08% | 0.09% | 0.08% | 0.09% | 0.08% | 0.09% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.11% | 0.11% | 0.12% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.11% | 0.11% | 0.12% |
| | 0.08% | 0.08% | | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.09% | 0.09% | | 0.10% | 0.11% | 0.11% | 0.12% | 0.12% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.08% | 0.09% | 0.08% | 0.08% | 0.08% | | 0.08% | 0.08% | 0.09% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.10% | | 0.11% | 0.12% | 0.12% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.07% | 0.08% | 0.08% | 0.09% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.11% | 0.11% | 0.11% | 0.12% |
| | 0.08% | 0.08% | | 0.08% | 0.08% | | 0.08% | 0.08% | 0.07% | 0.08% | | 0.08% | 0.08% | | 0.08% | 0.09% | | 0.10% | 0.09% | | 0.10% | 0.10% | | 0.11% | 0.12% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.07% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | 0.10% | 0.10% | 0.12% | 0.12% |
| 0.11% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.08% | 0.08% | 0.08% | 0.08% | 0.08% | 0.09% | 0.09% | 0.09% | 0.09% | 0.09% | 0.10% | 0.10% | 0.10% | 0.10% | 0.11% | 0.11% | 0.12% |
| | 0.11% | 0.11% | | 0.11% | 0.11% | | 0.11% | 0.12% | 0.11% | 0.11% | | 0.11% | 0.12% | | 0.13% | 0.12% | | 0.13% | 0.14% | | 0.15% | 0.14% | | 0.16% | 0.17% |

**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 pattern 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 (1.6) absorbers in the assembly guide tubes, and the ability to model the core baffle and other core structures.

Figure 9 in Section 1.12 provides the complete core loading pattern in quarter core symmetry. Only Bank D is used in the problem, and incore instrumentation is not included.

**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 | 600 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 (yet undefined).
- 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) does 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.

## 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 used for 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 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% | 3.1000% |
| 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 (www.wikipedia.com). 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, greater than 3e9 particles are used, skipping 300 generations. This resulted in an eigenvalue uncertainty of

less than **2 pcm**. 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 | |
|---|---|---|
| | Uncontrolled | Controlled |
| 0.0 < 0.5 | 0.39% | 0.40% |
| 0.5 – 1.0 | 0.30% | 0.34% |
| > 1.0 | 0.23% | 0.25% |

***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 M3-2 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.

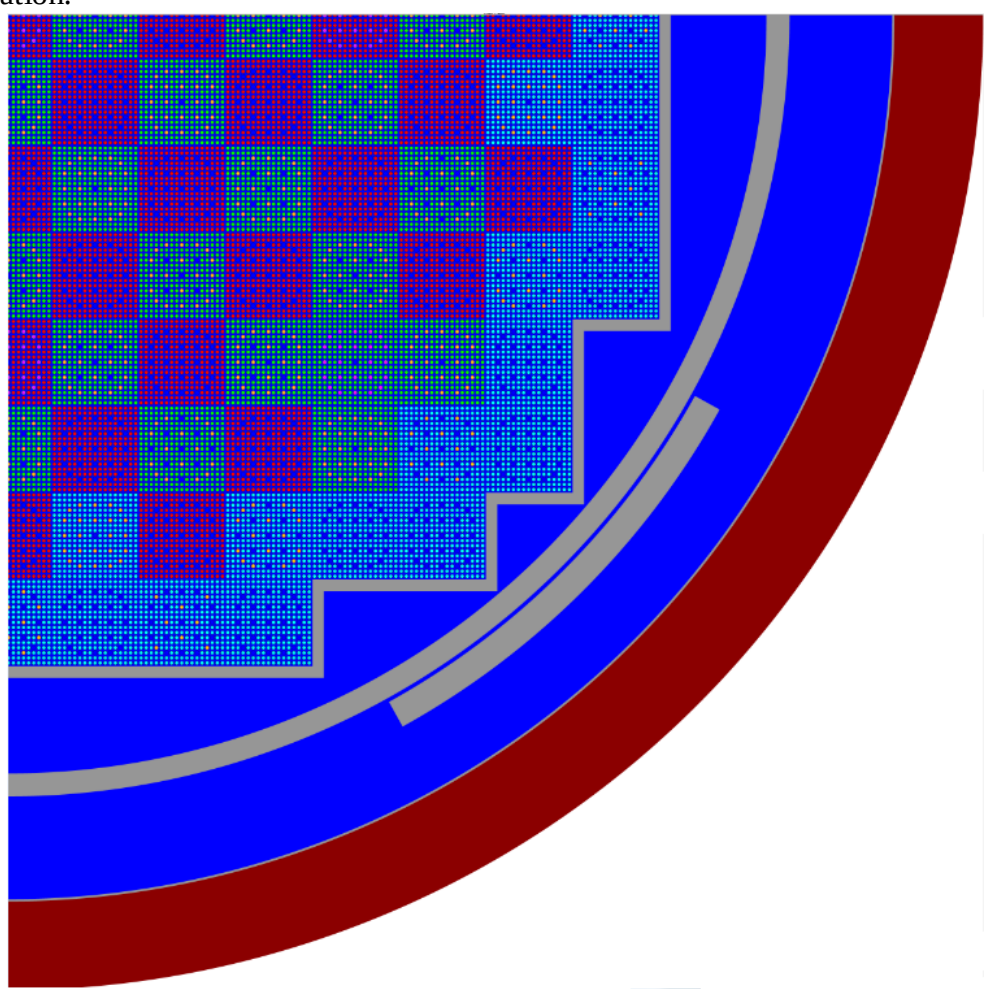


**Figure M3-2: Problem 5-2D Radial Geometry**

### *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 ~200 processors for ~40 hours.

### *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 |
| **3.11% 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 |
| **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 |

## REFERENCE SOLUTION RESULTS

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

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

Also, note that the reference KENO-VI results are calculated in 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 | Results |
|---|---|
| Uncontrolled | **1.002659 ± 0.000014** |
| Controlled | **0.990067 ± 0.000015** |
| Bank D Rod Worth | **-1268 ± 2 pcm** |

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

| Powers | Quantity | Uncontrolled | Controlled |
|---|---|---|---|
| Assembly Powers | Maximum | 1.3161 | 1.3055 |
| | Minimum | 0.6335 | 0.4415 |
| | Average Uncertainty | 0.17% | 0.18% |
| | Maximum Uncertainty | 0.22% | 0.28% |
| Pin Powers | Maximum | 1.4452 | 1.6061 |
| | Minimum | 0.1613 | 0.1650 |
| | Average Uncertainty | 0.17% | 0.180% |
| | Maximum Uncertainty | 0.39% | 0.396% |

***Uncontrolled***

| | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|
| 8 | 0.999 | 0.927 | 1.012 | 0.993 | 1.121 | 1.053 | 1.069 | 0.780 |
| 9 | 0.927 | 0.993 | 0.902 | 1.078 | 1.054 | 1.155 | 1.052 | 0.891 |
| 10 | 1.012 | 0.902 | 1.052 | 1.034 | 1.168 | 1.144 | 1.088 | 0.792 |
| 11 | 0.993 | 1.078 | 1.034 | 1.161 | 1.099 | 1.152 | 1.043 | 0.650 |
| 12 | 1.121 | 1.054 | 1.168 | 1.099 | 1.316 | 0.915 | 0.947 | |
| 13 | 1.053 | 1.155 | 1.144 | 1.152 | 0.915 | 0.927 | 0.634 | |
| 14 | 1.069 | 1.052 | 1.088 | 1.043 | 0.947 | 0.634 | | |
| 15 | 0.780 | 0.891 | 0.792 | 0.650 | | | | |

| | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|
| 8 | 0.18% | 0.17% | 0.17% | 0.17% | 0.16% | 0.16% | 0.16% | 0.20% |
| 9 | 0.17% | 0.17% | 0.17% | 0.16% | 0.16% | 0.15% | 0.16% | 0.18% |
| 10 | 0.17% | 0.17% | 0.16% | 0.16% | 0.15% | 0.15% | 0.16% | 0.19% |
| 11 | 0.17% | 0.16% | 0.16% | 0.15% | 0.16% | 0.15% | 0.16% | 0.22% |
| 12 | 0.16% | 0.16% | 0.15% | 0.16% | 0.15% | 0.17% | 0.17% | |
| 13 | 0.16% | 0.15% | 0.15% | 0.15% | 0.17% | 0.17% | 0.22% | |
| 14 | 0.16% | 0.16% | 0.16% | 0.16% | 0.17% | 0.22% | | |
| 15 | 0.20% | 0.18% | 0.19% | 0.22% | | | | |

***Controlled***

| | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|
| 8 | 0.442 | 0.742 | 0.927 | 0.825 | 0.557 | 1.027 | 1.286 | 1.005 |
| 9 | 0.742 | 0.877 | 0.853 | 0.991 | 0.940 | 1.217 | 1.272 | 1.149 |
| 10 | 0.927 | 0.853 | 1.036 | 1.011 | 1.162 | 1.242 | 1.306 | 1.004 |
| 11 | 0.825 | 0.991 | 1.011 | 1.074 | 0.947 | 1.150 | 1.188 | 0.795 |
| 12 | 0.557 | 0.940 | 1.162 | 0.947 | 0.622 | 0.788 | 0.996 | |
| 13 | 1.027 | 1.217 | 1.242 | 1.150 | 0.788 | 0.856 | 0.641 | |
| 14 | 1.286 | 1.272 | 1.306 | 1.188 | 0.996 | 0.641 | | |
| 15 | 1.005 | 1.149 | 1.004 | 0.795 | | | | |

| | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|
| 8 | 0.28% | 0.21% | 0.18% | 0.19% | 0.24% | 0.18% | 0.16% | 0.18% |
| 9 | 0.21% | 0.19% | 0.19% | 0.17% | 0.18% | 0.16% | 0.15% | 0.17% |
| 10 | 0.18% | 0.19% | 0.17% | 0.17% | 0.16% | 0.16% | 0.15% | 0.18% |
| 11 | 0.19% | 0.17% | 0.17% | 0.17% | 0.18% | 0.16% | 0.16% | 0.21% |
| 12 | 0.24% | 0.18% | 0.16% | 0.18% | 0.22% | 0.20% | 0.18% | |
| 13 | 0.18% | 0.16% | 0.16% | 0.16% | 0.20% | 0.19% | 0.23% | |
| 14 | 0.16% | 0.15% | 0.15% | 0.16% | 0.18% | 0.23% | | |
| 15 | 0.18% | 0.17% | 0.18% | 0.21% | | | | |

**Figure M3-3: Problem 5-2D Assembly Power Distributions and Uncertainties**

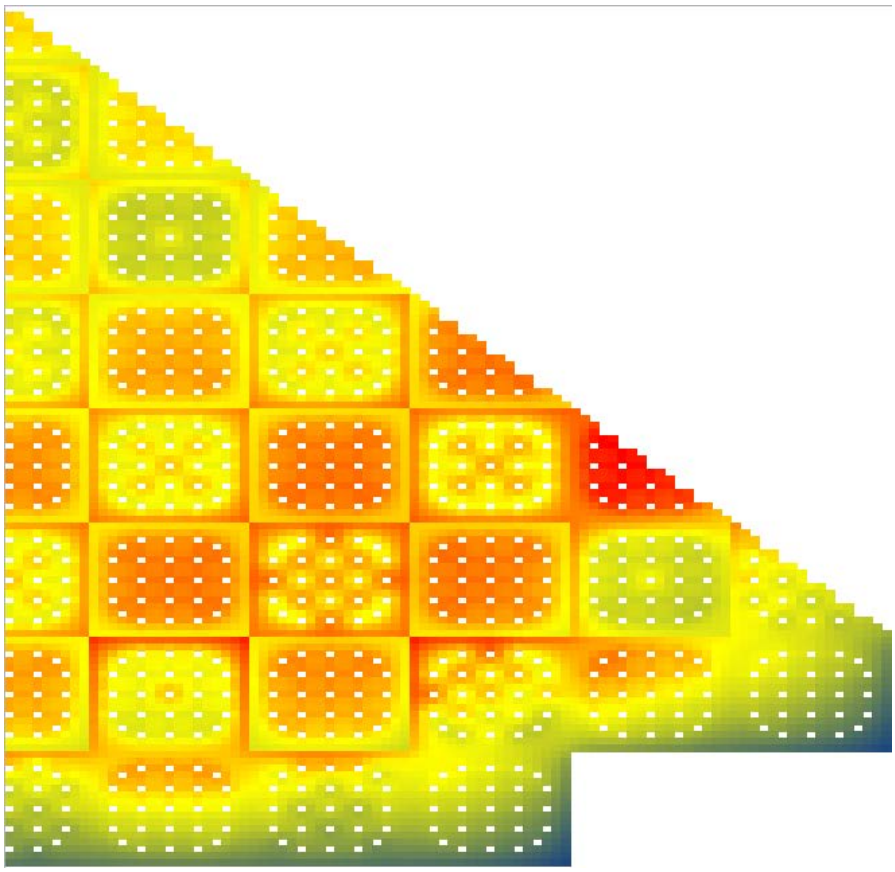


**Figure M3-4: Problem 5-2D Uncontrolled Pin Power Distribution**

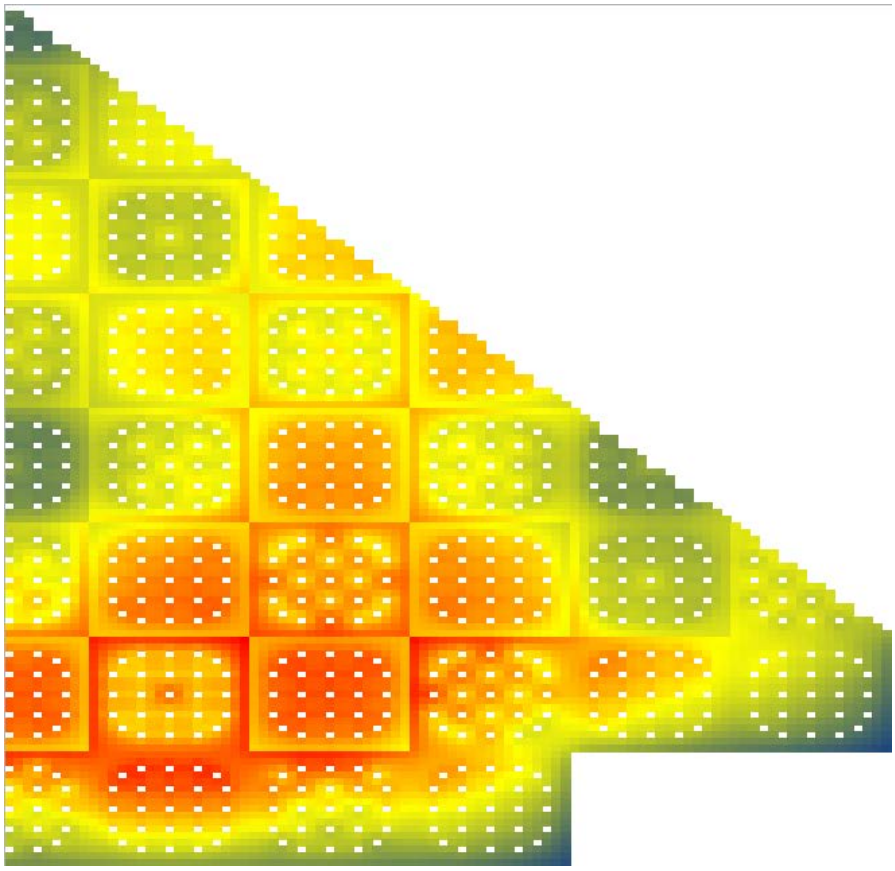


**Figure M3-5: Problem 5-2D Controlled Pin Power Distribution**

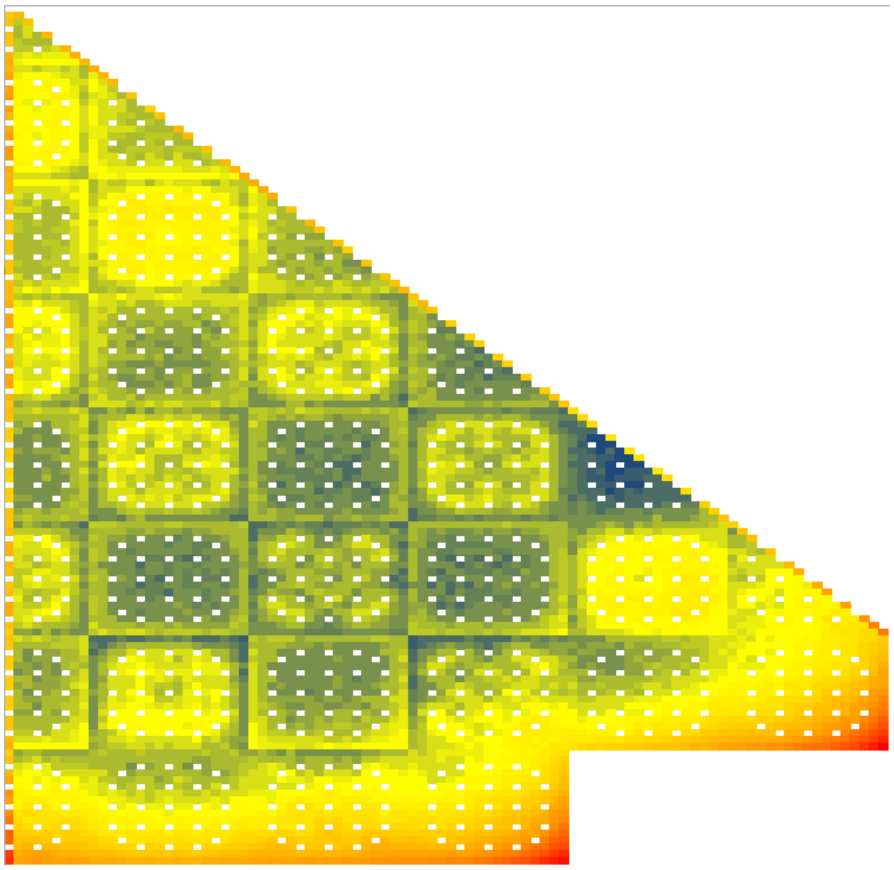


**Figure M3-6: Problem 5-2D Uncontrolled Pin Power Estimated Uncertainties**

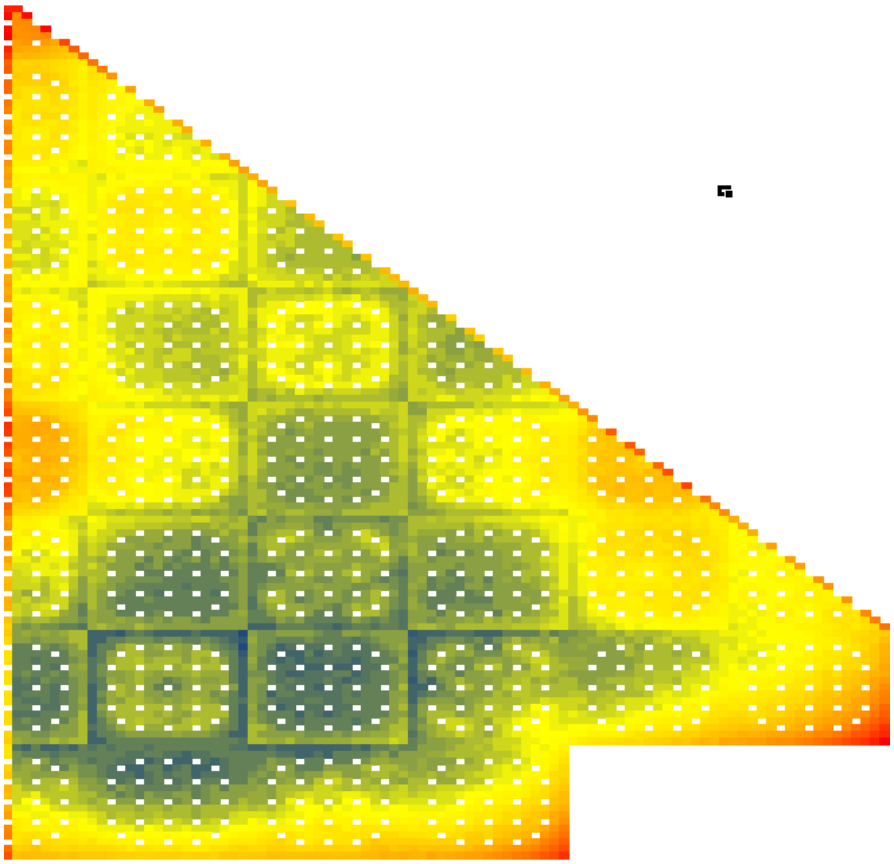


**Figure M3-7: Problem 5-2D Controlled Pin Power Estimated Uncertainties**

# REFERENCES


1 Watts Bar Unit 2 Final Safety Analysis Report (FSAR), Amendment 93, Section 4, ML091400651, April 30, 2009. http://adamswebsearch2.nrc.gov/idmws/ViewDocByAccession.asp?AccessionNumber=ML091400651

2 Watts Bar Unit 1 Cycle 2 Reload Safety Evaluation, TVA, ML073460287, August 1997. http://pbadupws.nrc.gov/docs/ML0734/ML073460287.pdf

3 www.matweb.com, as of January 31, 2012

4 www.steamtablesonline.com, as of January 31, 2012

5 Bowman, S.M.; Suto, T. Analysis of Pressurized Water Reactor Critical Configurations: Volume 5 - North Anna Unit 1 Cycle 5, ORNL/TM-12294/V5, October, 1996.

6 SCALE: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design, ORNL/TM-2005/39, Version 6.1, June 2011. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-785.

7 D. F. Hollenbach, L. M. Petrie, and N. F. Landers, "KENO-VI: A General Quadratic Version of the KENO Program," Vol. II, Sect. F17 of SCALE: A Modular Code System for Performing Standardized Computer Analysis for Licensing Evaluation, NUREG/CR-0200, Rev. 7 (ORNL/NUREG/CR/CSD-2R7), 3 vols., April 2004. Available from the Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-545.

8 Summary Report of Commercial Reactor Criticality Data for McGuire Unit 1, Revision 1, B00000000-01717-5705-00063, US DOE, April, 1998. http:/vv/pbadupws.nrc.gov/docs/ML0335/ML033520310.pdf

9 Luk, K.H., Pressurized-Water Reactor Internals Aging Degredation Study, NUREG/CR-6048 ORNL/TM-12371, US NRC, September, 1993. http://pbadupws.nrc.gov/docs/ML0403/ML040340653.pdf

10 Skaritka, J., Hybrid B4C Absorber Control Rod Evaluation Report, WCAP-8846, Westinghouse Electric Co, September, 1976.

11 Response to NRC Bulletin 88-09, "Thimble Tube Thinning in Westinghouse Reactors", Wisconsin Public Service Corporation, January, 1989. http://pbadupws.nrc.gov/docs/ML1116/ML111661598.pdf

12 Secker, Jeffrey R. and Jeffery A. Brown, "Westinghouse PWR Burnable Absorber Evolution and Usage", Westinghouse Electric Company, Winter ANS Conference, November 9, 2010.

13 Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty, EPRI, 1022909, August, 2011.

14 Enclosure D to FENOC Letter L-10-275, Licensing Report for Beaver Valley Unit 2 Rerack (Nonproprietary), Prepared by Holtec Intenational for First Entergy, HI-2084175, Rev. 6, October, 2010.

15 UK EPR, PCSR -- Sub-chapter 4.3 – Nuclear Design, UKEPR-0002-043 Issue 4, AREVA NP & EDF, March, 2011.

# 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   1.187820   0.000071
1B   1.182935   0.000071
1C   1.172386   0.000075
1D   1.163150   0.000069
1E   0.772366   0.000078

Case 1A @ 600K isothermal = 1.186186 +/- 0.000072
```

**Problem 1 ENDF/B-VI.8 Results**

```
Case   k-eff     Sigma
1A   1.183262  0.000106
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
```

Note that the temperature correction for problem 1A is based on the same 999 group ENDF/B-VII library as used for the ENDF/B-VII results in Revisions 0 and 1 of this document.

### *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=2750
 npg=40000
 nsk=250
 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 ENDF/B-VII.0 cross sections in ASCII form.

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

mixture = gaps and
plenums
  2004  2.68714E-05

mixture = Zircaloy-4
(clad, tubes, WABA,
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

mixture = moderator
(2A,2E-2P)
  1001  4.96224E-02
  8016  2.48112E-02
  5010  1.07070E-05
  5011  4.30971E-05

mixture = moderator
(2B-2D)
  1001  4.41459E-02
  8016  2.20729E-02
  5010  9.52537E-06
  5011  3.83408E-05

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 = 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

mixture = 3.6% fuel
(2K)
  8016  4.57669E-02
 92234  7.21203E-06
 92235  8.33952E-04
 92236  3.82913E-06
 92238  2.20384E-02

mixture = ifba (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

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 | 1.182733 | 0.000023 |
| 2B | 1.184033 | 0.000023 |
| 2C | 1.174434 | 0.000022 |
| 2D | 1.166137 | 0.000022 |
| 2E | 1.070441 | 0.000025 |
| 2F | 0.976903 | 0.000025 |
| 2G | 0.849236 | 0.000024 |
| 2H | 0.789746 | 0.000024 |
| 2I | 1.180561 | 0.000024 |
| 2J | 0.976101 | 0.000024 |
| 2K | 1.020999 | 0.000024 |
| 2L | 1.019538 | 0.000024 |
| 2M | 0.939462 | 0.000025 |
| 2N | 0.870430 | 0.000025 |
| 2O | 1.048367 | 0.000024 |
| 2P | 0.927999 | 0.000026 |

Case 2A @ 600K isothermal = 1.181390 +/- 0.000024

2A Radial Pin Powers

```
-----------------------------------
0.00000
1.03597 1.00854
1.03597 1.00926 1.00998
0.00000 1.03741 1.03886 0.00000
1.03525 1.00818 1.01143 1.04536 1.03236
1.03272 1.00565 1.00854 1.04572 1.05185 0.00000
0.00000 1.02622 1.02803 0.00000 1.03669 1.01828 0.97388
1.01143 0.98796 0.98796 1.01179 0.98291 0.96522 0.94790 0.93851
0.97605 0.97244 0.97172 0.97388 0.96450 0.95511 0.94609 0.94176 0.94790
```

2A Radial Pin Power 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%
```

2B Radial Pin Powers

```
-----------------------------------
0.00000
1.03530 1.01149
1.03566 1.01149 1.01149
0.00000 1.03602 1.03711 0.00000
1.03422 1.01005 1.01258 1.04288 1.03097
1.03133 1.00644 1.00969 1.04288 1.04757 0.00000
0.00000 1.02448 1.02592 0.00000 1.03242 1.01438 0.97398
1.01041 0.98913 0.98913 1.00969 0.98372 0.96640 0.94981 0.94079
0.97795 0.97434 0.97398 0.97542 0.96640 0.95666 0.94728 0.94332 0.94801
```

```
2B Radial 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 Radial Pin Powers
-----------------------------------
0.00000
1.03581 1.01108
1.03618 1.01145 1.01254
0.00000 1.03654 1.03727 0.00000
1.03399 1.00999 1.01254 1.04272 1.03072
1.03109 1.00672 1.00963 1.04236 1.04745 0.00000
0.00000 1.02454 1.02563 0.00000 1.03290 1.01472 0.97398
1.01072 0.98890 0.98890 1.00999 0.98380 0.96598 0.95034 0.94052
0.97799 0.97435 0.97326 0.97544 0.96671 0.95689 0.94707 0.94271 0.94780

2C Radial 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 Radial Pin Powers
-----------------------------------
0.00000
1.03665 1.01174
1.03591 1.01174 1.01247
0.00000 1.03665 1.03738 0.00000
1.03408 1.00954 1.01247 1.04287 1.03079
1.03152 1.00661 1.00954 1.04214 1.04727 0.00000
0.00000 1.02456 1.02602 0.00000 1.03298 1.01467 0.97364
1.01064 0.98903 0.98903 1.01027 0.98390 0.96595 0.94983 0.94068
0.97840 0.97401 0.97364 0.97511 0.96558 0.95643 0.94763 0.94287 0.94800

2D Radial 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 Radial Pin Powers
-----------------------------------
0.00000
1.01747 0.99232
0.92965 0.96318 0.99631
0.00000 0.93244 1.02505 0.00000
0.93524 0.96917 1.00270 1.03703 1.02824
1.02824 1.00310 0.97476 0.95160 1.02305 0.00000
0.00000 1.03543 0.94242 0.00000 0.95799 1.04301 1.03224
1.05858 1.02186 0.97675 0.93484 0.97875 1.01427 1.02385 1.02984
1.03503 1.02345 1.00589 0.99392 1.00549 1.02106 1.03184 1.03982 1.05140

2E Radial 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 Radial Pin Powers
-----------------------------------
0.00000
1.07686 1.04184
0.97180 0.99106 0.97355
0.00000 0.93328 0.92627 0.00000
0.92627 0.95910 0.95473 0.91183 0.92627
0.92802 0.96173 0.95867 0.91270 0.90701 0.00000
0.00000 0.94203 0.94116 0.00000 0.93547 0.96698 1.03396
0.97486 1.00463 1.00594 0.97880 1.01908 1.05016 1.08211 1.10925
1.04840 1.05322 1.05541 1.05541 1.07204 1.09174 1.11319 1.13376 1.15390

2F Radial 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 Radial Pin Powers
-----------------------------------
0.00000
1.07422 1.03540
0.93953 0.96609 0.94124
0.00000 0.88554 0.87672 0.00000
0.87354 0.92032 0.91478 0.85358 0.87238
0.87888 0.92687 0.92148 0.85600 0.85111 0.00000
0.00000 0.90888 0.90772 0.00000 0.90671 0.96478 1.07069
0.96438 1.00607 1.00919 0.97784 1.03893 1.09489 1.15185 1.19873
1.07069 1.08027 1.08581 1.08934 1.12009 1.15790 1.19974 1.23503 1.26527
```

```
2G Radial 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 Radial Pin Powers
-----------------------------------
0.00000
1.06069 1.02136
0.92228 0.94871 0.92196
0.00000 0.86482 0.85500 0.00000
0.85169 0.90004 0.89369 0.83151 0.85131
0.85940 0.90926 0.90340 0.83666 0.83449 0.00000
0.00000 0.89635 0.89618 0.00000 0.90253 0.97122 1.08951
0.96118 1.00454 1.01002 0.98055 1.04930 1.11446 1.18283 1.24034
1.07600 1.08625 1.09385 1.10144 1.13997 1.18717 1.23763 1.28158 1.31739

2H Radial Pin Uncertainties
-----------------------------------
0.000%
0.035%  0.030%
0.035%  0.021%  0.030%
0.000%  0.028%  0.021%  0.000%
0.035%  0.021%  0.025%  0.028%  0.040%
0.035%  0.021%  0.021%  0.028%  0.028%  0.000%
0.000%  0.021%  0.025%  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 Radial Pin Powers
-----------------------------------
0.00000
1.00498 0.99232
1.02559 1.00244 1.00678
0.00000 1.03427 1.03716 0.00000
1.03499 1.00859 1.01185 1.04548 1.03282
1.03282 1.00678 1.00968 1.04584 1.05199 0.00000
0.00000 1.02703 1.02884 0.00000 1.03716 1.01872 0.97568
1.01329 0.99015 0.99015 1.01257 0.98545 0.96700 0.95073 0.94097
0.97894 0.97460 0.97424 0.97641 0.96737 0.95760 0.94856 0.94494 0.94965

2I Radial 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 Radial Pin Powers
---------------------------------
0.00000
1.04092 1.02340
0.95944 0.98222 0.96907
0.00000 0.93008 0.92526 0.00000
0.92614 0.95944 0.95593 0.91300 0.92789
0.92877 0.96294 0.95944 0.91387 0.90818 0.00000
0.00000 0.94366 0.94279 0.00000 0.93709 0.96907 1.03654
0.97565 1.00631 1.00763 0.98134 1.02121 1.05231 1.08473 1.11189
1.04968 1.05538 1.05801 1.05801 1.07422 1.09437 1.11540 1.13555 1.15570

2J Radial Pin Uncertainties
----------------------------------
0.000%
0.028%  0.030%
0.028%  0.021%  0.030%
0.000%  0.021%  0.021%  0.000%
0.032%  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 Radial Pin Powers
-----------------------------------
0.00000
0.97684 1.06267
0.98940 1.00489 0.98563
0.00000 0.94585 0.93874 0.00000
0.93748 0.96888 0.96553 0.92366 0.93874
0.93874 0.97098 0.96805 0.92492 0.91948 0.00000
0.00000 0.95130 0.95088 0.00000 0.94711 0.98061 1.05011
0.98144 1.01075 1.01159 0.98772 1.02876 1.06435 1.10706 1.01494
1.05179 1.05807 1.06058 1.06225 1.08110 1.10915 1.01494 1.04467 1.06853

2K Radial 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 Radial Pin Powers
----------------------------------
0.00000
0.94834 0.99698
1.03261 1.00033 0.93073
0.00000 0.95589 1.02884 0.00000
0.96008 1.00913 1.01081 0.94080 0.98188
1.04771 1.02171 1.01626 0.93996 0.93912 0.00000
0.00000 0.96931 1.04645 0.00000 0.95421 1.03303 0.93912
0.96427 1.01962 1.02758 0.96511 1.01542 1.02297 1.00955 1.00788
1.03052 1.03639 1.03722 1.03052 1.03387 1.03513 1.02590 1.00243 0.90474
```

```
2L Radial 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 Radial Pin Powers
-----------------------------------
0.00000
0.98346 1.03900
0.98346 1.03900 1.03900
0.00000 0.98346 0.98209 0.00000
0.98255 1.03718 1.03627 0.97617 1.02079
0.98118 1.03627 1.03445 0.97116 0.96980 0.00000
0.00000 0.97799 0.97754 0.00000 0.96980 0.96616 1.00440
0.97299 1.01943 1.03035 0.97890 1.01715 1.01624 0.94385 1.01533
1.00713 0.94339 1.03354 1.02899 0.94703 1.03217 1.03627 1.02990 0.94157

2M Radial 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%

2N Radial Pin Powers
-----------------------------------
0.00000
0.97542 1.02681
0.89969 0.99632 1.02190
0.00000 0.89202 0.96598 0.00000
0.86994 0.97193 1.00567 0.94680 0.95561
0.86728 0.96436 0.96982 0.86522 0.84643 0.00000
0.00000 0.88204 0.88268 0.00000 0.87014 0.91090 1.05534
0.92482 1.01550 1.01845 0.93151 1.03616 1.08238 1.12763 1.15369
1.08091 1.09271 1.09615 1.09222 1.11877 1.14582 1.16648 1.16057 1.05927

2N Radial 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 Radial Pin Powers
-----------------------------------
0.00000
1.10581 1.07035
1.08828 1.05038 1.01818
0.00000 1.04141 0.98068 0.00000
1.04712 0.96519 0.21684 0.98802 1.03693
1.07402 1.02266 0.97701 1.05568 1.08136 0.00000
0.00000 1.09277 1.08258 0.00000 1.07932 0.99291 0.21668
1.10500 1.07728 1.07320 1.09195 1.04712 0.99250 0.92525 0.96356
1.07809 1.07117 1.06750 1.06383 1.04345 1.01655 0.99291 0.99984 1.01736

2O Radial 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 Radial Pin Powers
------------------------------------
0.00000
1.16803 1.11087
1.14176 1.05326 0.24319
0.00000 1.11825 1.06386 0.00000
1.06616 1.08276 1.08783 1.06294 0.24329
0.24499 1.04035 1.09566 1.10857 1.06063 0.00000
0.00000 1.11456 1.10673 0.00000 1.08091 1.03805 0.24218
1.14775 1.10903 1.03297 0.24319 1.00762 1.04081 1.00532 1.06109
1.13346 1.11456 1.06478 0.99518 1.04358 1.07492 1.08183 1.10534 1.13023

2P Radial 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%

2Q Radial Pin Powers
------------------------------------
0.00000
1.03663 1.01005
1.03735 1.01077 1.01150
0.00000 1.03808 1.03918 0.00000
1.03663 1.00932 1.01223 1.04464 1.03262
1.03262 1.00640 1.00932 1.04500 1.05119 0.00000
0.00000 1.02607 1.02789 0.00000 1.03553 1.01624 0.97218
1.01150 0.98784 0.98820 1.01114 0.98274 0.96380 0.94705 0.93722
0.97728 0.97291 0.97254 0.97436 0.96453 0.95470 0.94560 0.94123 0.94742
```

```
2Q Radial Pin Power 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%

2A @ 600K Radial Pin Powers – not an official problem
-----------------------------------
0.00000
1.03530 1.00965
1.03639 1.01001 1.01037
0.00000 1.03675 1.03820 0.00000
1.03494 1.00892 1.01145 1.04434 1.03205
1.03133 1.00603 1.00965 1.04434 1.05012 0.00000
0.00000 1.02555 1.02699 0.00000 1.03494 1.01651 0.97423
1.01145 0.98797 0.98869 1.01109 0.98363 0.96556 0.94894 0.93954
0.97712 0.97279 0.97243 0.97423 0.96520 0.95580 0.94677 0.94280 0.94822

2A @ 600K Radial 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%
```

# 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 ENDF/B-VI.8 cross sections in ASCII form.

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

mixture = gaps and
plenums
  2004  2.68714E-05

mixture = Zircaloy-4
(clad, tubes, WABA)
 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
(2A,2E-2P)
  1001  4.96224E-02
  8016  2.48112E-02
  5010  1.07070E-05
  5011  4.30971E-05

mixture = moderator
(2B-2D)
  1001  4.41459E-02
  8016  2.20729E-02
  5010  9.52537E-06
  5011  3.83408E-05
```

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

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

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

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

mixture = 3.6% fuel
(2K)
  8016  4.57669E-02
 92234  7.21203E-06
 92235  8.33952E-04
 92236  3.82913E-06
 92238  2.20384E-02
```

```
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  1.178280  0.000032 *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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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%

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

```
2A @ 600K Radial 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 Radial 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 Radial 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 Radial 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 Radial 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 Radial 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% |

# APPENDIX D – 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%)
  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 =  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 = 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
```

**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 |
|---|---|---|
| Uncontrolled | 1.010925 | 0.000023 |
| Controlled | 0.984155 | 0.000025 |

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

| Case | k-eff | Sigma |
|---|---|---|
| Uncontrolled | 1.007160 | 0.000024 |
| Controlled | 0.980355 | 0.000026 |

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

```
Assembly Radial Powers
-------------------------------------
 0.99779 0.92282     0.068%  0.067%
 0.92282 1.07773     0.067%  0.061%


Radial Pin Powers
-----------------------------------
Assembly:[1,1] H-8
0.00000
1.07341 1.05248
1.07075 1.04792 1.04868
0.00000 1.06847 1.06809 0.00000
1.06200 1.03993 1.04031 1.06580 1.05172
1.04906 1.02889 1.03042 1.05857 1.05933 0.00000
0.00000 1.02927 1.02965 0.00000 1.03460 1.01596 0.97486
0.99008 0.97296 0.97410 0.99198 0.97182 0.95812 0.94214 0.92996
0.92083 0.91778 0.91855 0.92311 0.91931 0.91817 0.91664 0.91512 0.91626

Assembly:[1,2] H-9
1.00949 1.01291 1.01405 1.01443 1.02280 1.03232 1.04525 1.06086 1.08521
0.89419 0.92197 0.92501 0.89876 0.93377 0.96078 0.99198 1.02280 1.06466
0.00000 0.84511 0.84891 0.00000 0.84244 0.86908 0.93605 0.99389 1.05210
0.82646 0.86451 0.87403 0.84359 0.82646 0.00000 0.87250 0.96687 1.04297
0.83027 0.87403 0.91284 0.93110 0.88811 0.82798 0.84853 0.94176 1.03612
0.00000 0.85919 0.94328 0.00000 0.93301 0.84663 0.00000 0.90865 1.02851
0.86832 0.89990 0.92768 0.94480 0.91512 0.87973 0.85690 0.93757 1.03156
0.95279 0.92958 0.90028 0.86109 0.87669 0.87022 0.85386 0.93719 1.03270
0.00000 0.95241 0.86832 0.00000 0.83293 0.83179 0.00000 0.90789 1.02927
0.95127 0.92844 0.89876 0.85881 0.87517 0.86946 0.85386 0.93757 1.03460
0.86375 0.89533 0.92311 0.94138 0.91322 0.87821 0.85652 0.93909 1.03726
0.00000 0.85196 0.93567 0.00000 0.92806 0.84549 0.00000 0.91132 1.03536
0.81733 0.86071 0.90028 0.92121 0.88011 0.82532 0.84701 0.94594 1.04335
0.80744 0.84397 0.85500 0.82760 0.81391 0.00000 0.86908 0.96953 1.05363
0.00000 0.80972 0.81467 0.00000 0.81847 0.84967 0.92387 0.99389 1.06428
0.83027 0.85804 0.86261 0.84206 0.88506 0.92045 0.96459 1.01291 1.07341
0.89115 0.89724 0.90294 0.90599 0.92730 0.95584 0.99046 1.03232 1.08673
```

```
Assembly:[2,2] G-9
0.91855
0.92159 0.93909
0.92539 0.95584 0.99236
0.93034 0.97296 1.03688 0.00000
0.93529 0.99084 1.05857 1.08863 1.08445
0.93871 1.01405 0.00000 1.09054 1.10347 0.00000
0.93795 0.99769 1.05857 1.06466 1.07874 1.11337 1.09662
0.93985 1.00035 1.06086 1.06618 1.08216 1.11717 1.10271 1.10956
0.94366 1.01976 0.00000 1.09092 1.10918 0.00000 1.13049 1.13696 0.00000
0.94480 1.00492 1.06770 1.07151 1.09092 1.12668 1.11260 1.11945 1.14837 1.13087
0.94518 1.00758 1.07075 1.07912 1.09586 1.13125 1.11679 1.12326 1.15370 1.13658 1.14228
0.94937 1.02851 0.00000 1.11337 1.12783 0.00000 1.14343 1.15066 0.00000 1.16397 1.16968 0.00000
0.94937 1.00987 1.08445 1.11755 1.12021 1.14305 1.12478 1.12935 1.15789 1.14152 1.14875 1.18338 1.17577
0.94708 0.99921 1.07113 0.00000 1.13734 1.14457 1.12250 1.12897 1.15941 1.14114 1.14913 1.18604 1.19213 0.00000
0.94708 0.98780 1.03612 1.09320 1.12516 0.00000 1.13962 1.14647 0.00000 1.15865 1.16626 0.00000 1.17995 1.16626 1.12706
0.94975 0.98361 1.01596 1.05020 1.07912 1.11489 1.10576 1.11222 1.14000 1.12630 1.13239 1.15560 1.13429 1.11945 1.10499 1.09738
0.95736 0.98704 1.01481 1.04145 1.06276 1.08445 1.09130 1.10005 1.11146 1.11222 1.11717 1.12250 1.11755 1.11032 1.10309 1.09967 1.10423

 Radial Pin Uncertainties
-----------------------------------
Assembly:[1,1] H-8
0.000%
0.085%  0.090%
0.085%  0.064%  0.090%
0.000%  0.060%  0.060%  0.000%
0.085%  0.060%  0.064%  0.064%  0.090%
0.085%  0.060%  0.064%  0.064%  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%  0.060%  0.060%  0.064%  0.060%  0.057%
0.092%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%
0.000%  0.064%  0.071%  0.000%  0.071%  0.064%  0.067%  0.064%  0.060%
0.099%  0.067%  0.064%  0.067%  0.071%  0.000%  0.064%  0.064%  0.064%
0.099%  0.067%  0.064%  0.064%  0.067%  0.067%  0.071%  0.064%  0.064%
0.000%  0.064%  0.064%  0.000%  0.064%  0.071%  0.000%  0.064%  0.064%
0.092%  0.064%  0.064%  0.064%  0.064%  0.067%  0.064%  0.064%  0.064%
0.092%  0.064%  0.064%  0.071%  0.067%  0.067%  0.064%  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%  0.071%  0.067%  0.064%  0.067%  0.064%  0.060%
0.095%  0.064%  0.064%  0.064%  0.064%  0.064%  0.067%  0.064%  0.060%
0.000%  0.071%  0.064%  0.000%  0.064%  0.067%  0.000%  0.064%  0.060%
0.099%  0.071%  0.064%  0.064%  0.064%  0.067%  0.071%  0.064%  0.064%
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%  0.067%  0.064%  0.064%  0.064%
0.099%  0.071%  0.064%  0.067%  0.064%  0.064%  0.064%  0.064%  0.060%
0.092%  0.064%  0.067%  0.064%  0.064%  0.064%  0.064%  0.064%  0.060%
```

```
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%  0.060%  0.057%  0.090%
0.064%  0.064%  0.000%  0.060%  0.057%  0.000%
0.064%  0.064%  0.064%  0.060%  0.060%  0.057%  0.090%
0.064%  0.064%  0.060%  0.064%  0.060%  0.060%  0.060%  0.090%
0.064%  0.064%  0.000%  0.057%  0.060%  0.000%  0.057%  0.057%  0.000%
0.064%  0.064%  0.057%  0.060%  0.057%  0.060%  0.060%  0.057%  0.057%  0.080%
0.064%  0.064%  0.060%  0.060%  0.060%  0.060%  0.057%  0.057%  0.057%  0.057%  0.080%
0.064%  0.064%  0.000%  0.057%  0.057%  0.000%  0.060%  0.057%  0.000%  0.057%  0.057%  0.000%
0.064%  0.064%  0.064%  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%  0.057%  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%  0.064%  0.060%  0.064%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.060%  0.057%  0.057%  0.080%
0.064%  0.064%  0.064%  0.064%  0.060%  0.060%  0.057%  0.060%  0.060%  0.057%  0.060%  0.057%  0.060%  0.060%  0.060%  0.060%  0.090%
```

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

```
Assembly Radial Powers
--------------------------
 0.57132 0.92640     0.091%  0.067%
 0.92640 1.18077     0.067%  0.060%
```

```
Radial Pin Powers
---------------------------------
 Assembly:[1,1] H-8
0.00000
0.55190 0.53536
0.48649 0.50326 0.49103
0.00000 0.46268 0.45948 0.00000
0.46331 0.48989 0.48849 0.45760 0.47469
0.47050 0.50311 0.50151 0.46612 0.47058 0.00000
0.00000 0.50420 0.50542 0.00000 0.51793 0.56347 0.63834
0.55487 0.57950 0.58443 0.56965 0.61273 0.65503 0.70171 0.74374
0.63263 0.63900 0.64381 0.65050 0.67552 0.70542 0.74131 0.77540 0.80848
```

```
Assembly:[1,2] H-9
0.77908 0.78580 0.79167 0.80105 0.82685 0.85930 0.89878 0.94179 0.99066
0.74170 0.76903 0.77489 0.75902 0.80339 0.84405 0.89058 0.94101 0.99965
0.00000 0.74495 0.75183 0.00000 0.75969 0.79362 0.86868 0.94023 1.01255
0.75965 0.79518 0.80769 0.78580 0.77329 0.00000 0.83350 0.93749 1.02271
0.78463 0.82724 0.86634 0.89018 0.85344 0.80339 0.82646 0.93045 1.03210
0.00000 0.83311 0.91638 0.00000 0.91481 0.83623 0.00000 0.91247 1.04304
0.86008 0.89058 0.91755 0.93788 0.91208 0.88197 0.86555 0.95469 1.05829
0.95782 0.93553 0.90621 0.86751 0.88784 0.88549 0.87416 0.96564 1.07197
0.00000 0.96876 0.88549 0.00000 0.85500 0.85852 0.00000 0.94765 1.08136
0.98049 0.95704 0.92850 0.89058 0.91012 0.90817 0.89527 0.98870 1.09660
0.89957 0.93319 0.96251 0.98362 0.95743 0.92420 0.90504 0.99887 1.10755
0.00000 0.89605 0.98479 0.00000 0.97893 0.89566 0.00000 0.97658 1.11381
0.86555 0.91090 0.95352 0.97619 0.93514 0.88119 0.90739 1.01998 1.12905
0.85734 0.89839 0.91051 0.88315 0.87025 0.00000 0.93632 1.04930 1.14274
0.00000 0.86712 0.87220 0.00000 0.87924 0.91716 0.99965 1.07745 1.15798
0.88940 0.92068 0.92576 0.90621 0.95352 0.99535 1.04656 1.10129 1.17206
0.95664 0.96407 0.96994 0.97619 1.00082 1.03366 1.07432 1.12280 1.18769

 Assembly:[2,2] G-9
0.86321
0.88471 0.91560
0.90582 0.94883 0.99691
0.92498 0.98127 1.05555 0.00000
0.94413 1.01060 1.09113 1.13062 1.13765
0.96173 1.04617 0.00000 1.14508 1.16697 0.00000
0.97072 1.04226 1.11576 1.12866 1.15290 1.19708 1.18848
0.98362 1.05438 1.12553 1.13765 1.16463 1.20841 1.19942 1.21350
0.99809 1.08409 0.00000 1.17401 1.20216 0.00000 1.23774 1.25142 0.00000
1.00551 1.07784 1.15016 1.16306 1.18809 1.23187 1.22210 1.23852 1.27566 1.26119
1.01372 1.08683 1.16267 1.17518 1.20138 1.24516 1.23422 1.24751 1.28660 1.27097 1.27996
1.02662 1.11615 0.00000 1.21741 1.24125 0.00000 1.27018 1.28152 0.00000 1.30537 1.31671 0.00000
1.02858 1.10129 1.18613 1.22992 1.23461 1.26706 1.25025 1.26315 1.29990 1.28308 1.29638 1.33899 1.33313
1.03288 1.09309 1.17636 0.00000 1.25885 1.27057 1.25376 1.26471 1.30263 1.28543 1.29990 1.34329 1.35580 0.00000
1.03562 1.08566 1.14117 1.20841 1.24790 0.00000 1.27448 1.28621 0.00000 1.31123 1.31983 0.00000 1.34212 1.32687 1.28621
1.03953 1.08018 1.12162 1.16346 1.20020 1.24399 1.23734 1.25064 1.28621 1.27370 1.28308 1.31319 1.28973 1.27722 1.26002 1.25259
1.04891 1.08683 1.12084 1.15446 1.18378 1.20959 1.22327 1.23695 1.25220 1.25767 1.26745 1.27683 1.27175 1.26627 1.25846 1.25572 1.26354

Radial Pin Uncertainties
---------------------------------
 Assembly:[1,1] H-8
0.000%
0.120%  0.120%
0.124%  0.088%  0.130%
0.000%  0.088%  0.088%  0.000%
0.127%  0.088%  0.088%  0.092%  0.130%
0.127%  0.092%  0.085%  0.092%  0.092%  0.000%
0.000%  0.088%  0.085%  0.000%  0.085%  0.081%  0.110%
0.117%  0.081%  0.081%  0.085%  0.078%  0.078%  0.071%  0.110%
0.113%  0.078%  0.078%  0.078%  0.078%  0.078%  0.071%  0.071%  0.100%
```

```
 Assembly:[1,2] H-9
0.099%  0.071%  0.071%  0.071%  0.071%  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%  0.074%  0.000%  0.074%  0.071%  0.071%  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%  0.067%  0.071%  0.071%  0.071%  0.064%  0.064%
0.000%  0.071%  0.064%  0.000%  0.064%  0.071%  0.000%  0.064%  0.064%
0.095%  0.071%  0.064%  0.064%  0.064%  0.071%  0.071%  0.064%  0.060%
0.092%  0.064%  0.064%  0.064%  0.064%  0.071%  0.064%  0.064%  0.064%
0.000%  0.064%  0.064%  0.000%  0.071%  0.071%  0.000%  0.064%  0.064%
0.092%  0.064%  0.064%  0.067%  0.064%  0.064%  0.064%  0.064%  0.060%
0.092%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.057%
0.000%  0.071%  0.064%  0.000%  0.064%  0.067%  0.000%  0.064%  0.057%
0.099%  0.064%  0.064%  0.064%  0.064%  0.067%  0.064%  0.064%  0.057%
0.095%  0.064%  0.067%  0.067%  0.067%  0.000%  0.064%  0.064%  0.057%
0.000%  0.067%  0.071%  0.000%  0.067%  0.064%  0.064%  0.060%  0.057%
0.092%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.060%  0.057%
0.092%  0.064%  0.064%  0.064%  0.064%  0.064%  0.064%  0.060%  0.057%

 Assembly:[2,2] G-9
0.100%
0.064%  0.090%
0.064%  0.064%  0.090%
0.064%  0.064%  0.064%  0.000%
0.064%  0.064%  0.060%  0.060%  0.080%
0.064%  0.060%  0.000%  0.057%  0.057%  0.000%
0.064%  0.064%  0.057%  0.057%  0.060%  0.057%  0.080%
0.064%  0.060%  0.060%  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%  0.060%  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%  0.080%
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%  0.057%  0.000%
0.064%  0.064%  0.057%  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%  0.057%  0.064%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  0.057%  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%
```

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

```
Assembly Radial Powers
------------------------
0.99842 0.92249     0.069%  0.067%
0.92249 1.07790     0.067%  0.061%
```

```
Radial 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
```

```
Radial Pin 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%
```

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

Assembly Radial Powers
---
0.57203 0.92652 0.091% 0.067%
0.92652 1.18048 0.067% 0.060%

Radial 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

Radial Pin 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% |

# APPENDIX E – 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
 92234  4.04814E-06
 92235  4.88801E-04
 92236  2.23756E-06
 92238  2.23844E-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
```

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

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

```
Assembly Radial 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
1.26522 1.21362 0.00000 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% | 0.080% | 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 F – 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
```

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

| Case | k-eff | Sigma |
|---|---|---|
| Uncontrolled | 1.002659 | 0.000014 |
| Controlled | 0.990067 | 0.000015 |

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

Assembly Radial Powers

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.99903 | 0.92652 | 1.01187 | 0.99327 | 1.12118 | 1.05266 | 1.06853 | 0.77966 |
| 0.92652 | 0.99342 | 0.90185 | 1.07832 | 1.05412 | 1.15513 | 1.05219 | 0.89124 |
| 1.01187 | 0.90185 | 1.05195 | 1.03448 | 1.16795 | 1.14371 | 1.08806 | 0.79157 |
| 0.99327 | 1.07832 | 1.03449 | 1.16104 | 1.09878 | 1.15234 | 1.04349 | 0.64989 |
| 1.12118 | 1.05412 | 1.16795 | 1.09878 | 1.31608 | 0.91450 | 0.94736 | |
| 1.05266 | 1.15513 | 1.14371 | 1.15234 | 0.91450 | 0.92712 | 0.63351 | |
| 1.06853 | 1.05219 | 1.08806 | 1.04349 | 0.94736 | 0.63351 | | |
| 0.77966 | 0.89124 | 0.79157 | 0.64989 | | | | |

Assembly Radial Uncertainties

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.176% | 0.173% | 0.165% | 0.167% | 0.157% | 0.162% | 0.161% | 0.197% |
| 0.173% | 0.166% | 0.171% | 0.156% | 0.158% | 0.151% | 0.160% | 0.180% |
| 0.165% | 0.171% | 0.162% | 0.160% | 0.150% | 0.152% | 0.156% | 0.192% |
| 0.167% | 0.156% | 0.160% | 0.154% | 0.155% | 0.151% | 0.161% | 0.218% |
| 0.157% | 0.158% | 0.150% | 0.155% | 0.145% | 0.170% | 0.172% | |
| 0.162% | 0.151% | 0.152% | 0.151% | 0.170% | 0.174% | 0.220% | |
| 0.161% | 0.160% | 0.156% | 0.161% | 0.172% | 0.220% | | |
| 0.197% | 0.180% | 0.192% | 0.218% | | | | |

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

Assembly Radial Powers

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.44154 | 0.74218 | 0.92739 | 0.82470 | 0.55654 | 1.02658 | 1.28605 | 1.00480 |
| 0.74218 | 0.87737 | 0.85319 | 0.99144 | 0.94017 | 1.21698 | 1.27193 | 1.14901 |
| 0.92739 | 0.85319 | 1.03571 | 1.01101 | 1.16226 | 1.24224 | 1.30553 | 1.00355 |
| 0.82470 | 0.99144 | 1.01101 | 1.07412 | 0.94749 | 1.15014 | 1.18768 | 0.79536 |
| 0.55654 | 0.94017 | 1.16226 | 0.94749 | 0.62194 | 0.78839 | 0.99588 | |
| 1.02658 | 1.21698 | 1.24224 | 1.15014 | 0.78839 | 0.85600 | 0.64086 | |
| 1.28605 | 1.27193 | 1.30553 | 1.18768 | 0.99588 | 0.64086 | | |
| 1.00480 | 1.14901 | 1.00355 | 0.79536 | | | | |

Assembly Radial Uncertainties

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 0.280% | 0.205% | 0.182% | 0.194% | 0.235% | 0.175% | 0.155% | 0.183% |
| 0.205% | 0.188% | 0.187% | 0.173% | 0.179% | 0.156% | 0.153% | 0.168% |
| 0.182% | 0.187% | 0.173% | 0.171% | 0.159% | 0.155% | 0.151% | 0.180% |
| 0.194% | 0.173% | 0.171% | 0.170% | 0.178% | 0.161% | 0.160% | 0.208% |
| 0.235% | 0.179% | 0.159% | 0.178% | 0.222% | 0.195% | 0.178% | |
| 0.175% | 0.156% | 0.155% | 0.161% | 0.195% | 0.192% | 0.230% | |
| 0.155% | 0.153% | 0.151% | 0.160% | 0.178% | 0.230% | | |
| 0.183% | 0.168% | 0.180% | 0.208% | | | | |