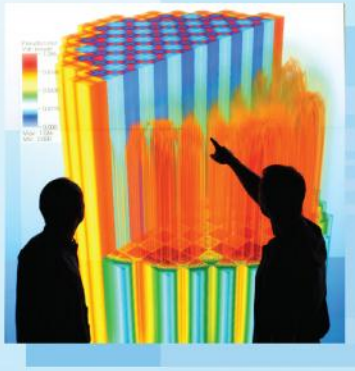
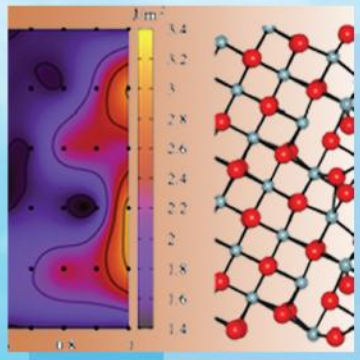
CASL-U-2012-0131-000

Power uprates
and plant life extension



Engineering design
and analysis

Science-enabling
high performance
computing



Fundamental science

Plant operational data

Consortium for Advanced Simulation of LWRs

VERA Core Physics Benchmark Progression Problem Specifications

Revision 0

August 31st, 2012

Andrew T. Godfrey
Advanced Modeling Applications
Oak Ridge National Laboratory

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

REVISION LOG

Revision	Date	Affected Pages	Revision Description
0	8/31/2012	All	Original Release

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 4. These problems were selected to assist developers and analysts in progressing through capabilities needed to model nuclear reactors and their operations. The problems provide a prioritization of the VERA requirements for the virtual reactor. 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 4 represent geometries that are contained in the WBN1 initial core. 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 vii

ACRONYMS ix

INTRODUCTION 1

1. GEOMETRY 2

2. MATERIALS 10

3. OPERATING CONDITIONS 10

PROBLEMS 11
Problem #1: HZP BOC Pin Cell 11
Problem #2: HZP BOC Fuel Lattice 16
Problem #3: 3D HZP Assembly 31
Problem #4: 3D HZP 3x3 Assembly Control Rod Worth 43

REFERENCES 46

FIGURES

Figure 1. Fuel Rod Arrangement ii

Figure 2: 17x17 Lattice Fuel Rod and Thimble Arrangement 3

Figure 3. Axial Fuel Assembly Arrangement 5

Figure 4. Pyrex Configurations (Octant Symmetry) 7

Figure 5. RCCA Assembly 8

Figure P1-1: Problem 1 KENO-VI Geometry 11

Figure P2-1: Problem 2 Lattice Layouts (Octant Symmetry) 18

Figure P2-2: Problem 2A CE KENO-VI Power Distribution Results 26

Figure P2-3: Problem 2B CE KENO-VI Power Distribution Results 26

Figure P2-4: Problem 2C CE KENO-VI Power Distribution Results 27

Figure P2-5: Problem 2D CE KENO-VI Power Distribution Results 27

Figure P2-6: Problem 2E CE KENO-VI Power Distribution Results 28

Figure P2-7: Problem 2F CE KENO-VI Power Distribution Results 28

Figure P2-8: Problem 2G CE KENO-VI Power Distribution Results 29

Figure P2-9: Problem 2H CE KENO-VI Power Distribution Results 29

Figure P2-10: Problem 2I CE KENO-VI Power Distribution Results 30

Figure P2-11: Problem 2J CE KENO-VI Power Distribution Results 30

Figure P3-1: Problem 3 Axial Geometry (without plugs) 32

Figure P3-2: Problem 3 Reference Model 35

Figure P3-3: Problem 3 Axial Power 40

Figure P3-4: Problem 3 Radial Power Distribution 41

Figure P3-5: Problem 3 Visualization of Pin Power Results and Uncertainties 42

Figure P4-1: Problem 4 Assembly, Poison, and Control Layout 43

Figure P4-2: Problem 4 Radial Geometry (a single 2D slice) 44

TABLES

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

Table 2: 17x17 Lattice Specification (Ref. 1) 3

Table 3: Spacer Grid Specification 4

Table 4: Fuel Assembly Specification (Ref. 1) 5

Table 5: Assembly Nozzle and Core Plate Specification 6

Table 6: Pyrex Rod Specification vi

Table 7: Pyrex Isotopics 7

Table 8: RCCA Rod and Drive Specification viii

Table 9: Thimble Plug Specification 9

Table 10: Instrument Thimble Specification ix

Table 11: Example LEU Isotopic Equations 10

Table P1-1: Problem 1 Calculations 11

Table P1-2: Problem 1 Input Specification 11

Table P1-3: Problem 1 Calculated Isotopic Input 13

Table P1-4: Reference Mixing Table 14

Table P1-5: 999g Temperature Correction Results 15

Table P1-6: Problem 2 Reference Solution Results 15

Table P2-1: Problem 2 Calculations 16

Table P2-2: Problem 2 Input Specification 17

Table P2-3: Problem 2 Calculated Isotopic Input 20

Table P2-4: Reference Mixing Table 23

Table P2-5: 999g Temperature Correction Results 25

Table P2-6: Problem 2 Reference Solution Eigenvalue Results 25

Table P3-1: Problem 3 Statepoint Specification 31

Table P3-2: Problem 3 Calculated Isotopic Input 33

Table P3-3: Reference Mixing Table 36

Table P3-4: Problem 3 Axial Powers 39

Table P4-1: Problem 4 Input Specification 43

Table P4-2: Problem 4 Calculated Isotopic Input 45

ACRONYMS

2D	Two-Dimensional
3D	Three-Dimensional
AIC	Silver-Indium Cadmium control rods
AMA	CASL's Advanced Modeling Applications Focus Area
B_4C	Boron Carbide control rods
BOL	Beginning-of-Life
CE	Continuous energy (as in cross sections)
CFD	Computational Fluid Dynamics
FP	Full Power
HFP	Hot Full Power
HZP	Hot Zero Power
MG	Multi-group (as in cross sections)
PCM	Percent milli (10^{-5})
PWR	Pressurized Water Reactor
RCCA	Rod Cluster Control Assembly
VERA	Virtual Environment for Reactor Applications
WBN1	Watts Bar Nuclear 1 (here Cycle 1)

INTRODUCTION

The AMA Core Physics Benchmark Progression Problems 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 four problems, ranging from a simple 2D pin cell to a multi-assembly configuration with control rods and burnable poisons. All of the data in this document is publicly available and is based on actual fuel and plant data from the initial core loading of Watts Bar Nuclear 1.

In addition to defining a common specification to test each level of capability, the document also provides a reference solution, when possible, based on continuous energy Monte Carlo methods using ENDF/B-VII cross sections. This is important for the first four problems to define an analytical standard so that we can understand capability in context of accuracy.

Each problem may be solved to different degrees of satisfaction. The section entitles “Capabilities” provides a list of many required or desired features of an excellent reactor analysis tool that could be demonstrated at for problem. It should be discouraged to approach these problems as “solved” or “not solved”, but rather how well are they used, with what ease, and how comprehensive is the software demonstrating the capabilities that are suggested.

1. GEOMETRY

Each of problems in this specification is based on actual fuel and core geometries use in the in 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.

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 1 below presents the fuel rod geometry. Table 1 provides the detailed rod data as is possible from the source.

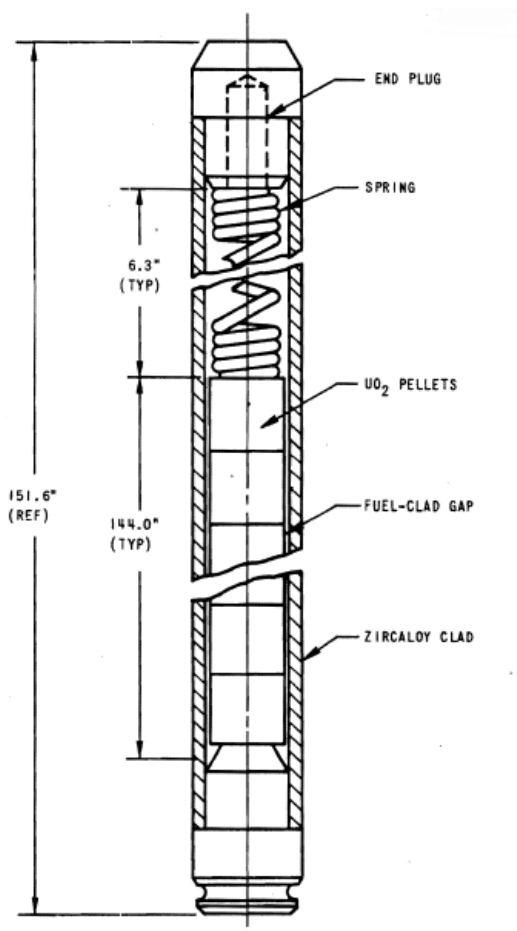


Figure 1. Fuel Rod Arrangement
(Ref. 1 Figure 4.2-3, in inches)

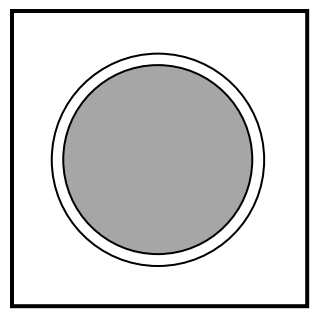


Table 1: Fuel Rod Specification (Ref. 1)

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 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 is assumed to extend the entire height between the top and bottom nozzle. These tubes are arranged in a fixed radial layout for all assemblies, shown in Figure 2. Table 2 provides the detailed guide tube and instrument tube specifications. The guide tube dashpot is ignored.

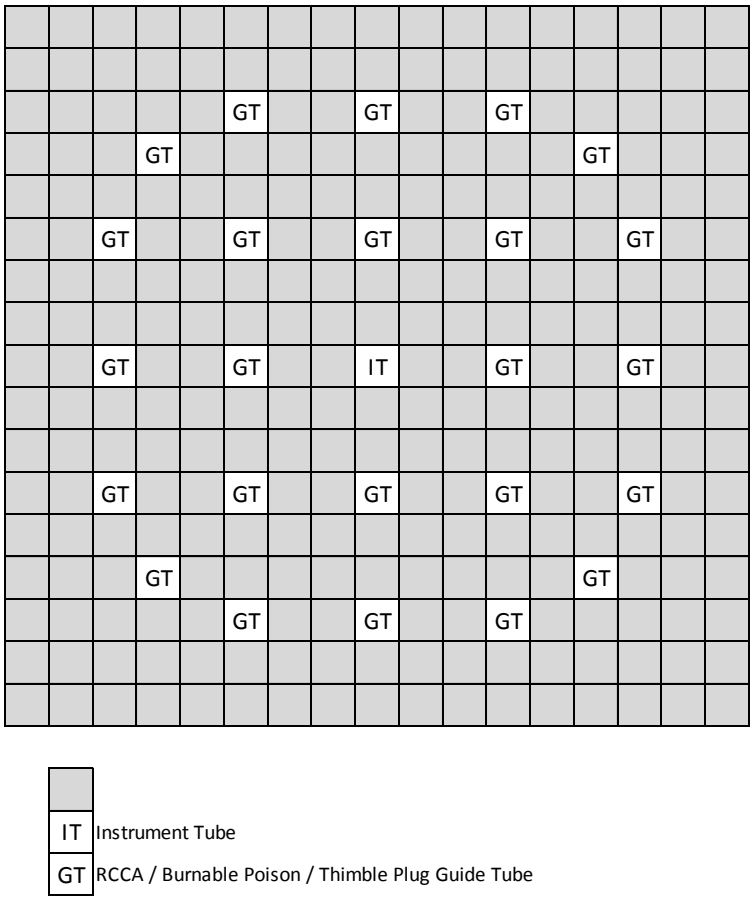


Figure 2: 17x17 Lattice Fuel Rod and Thimble Arrangement
(Ref. 1 Figure 4.2-1)

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 2 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 necessary made from the same material as the straps.

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 of spacer grids are not required for accurate reactivity and pin power calculations due to the thinness of the grid straps and the mean free path of neutrons. Different information will be needed for sub-channel or CFD analyses of the grids.

The data for WBN1 has not been located. The specification below in Table 3 is 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, considered as the same as 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)	13.884 388.2	75.2 127.4 179.6 231.8 284.0 336.2

- The spacer grid types, heights, and locations are obtained from Reference 1 (shown in Figure 3). 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 approximated 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).
- 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 3 provides a pictorial of the assembly and provides some of its axial elevations. The addition assembly specifications for the assembly are provided in Table 4 and specifications for the nozzles and core plates are given in Table 5.

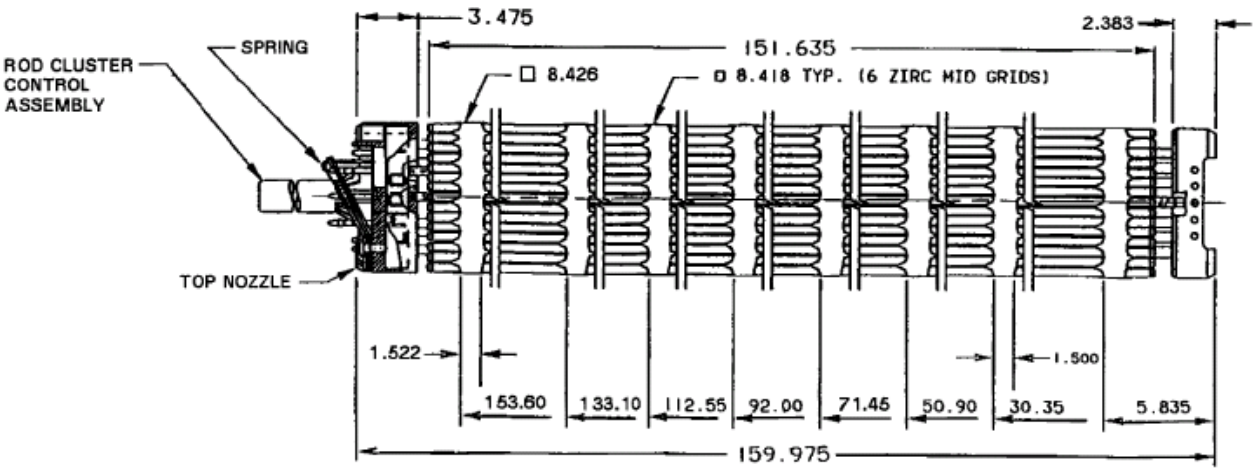


Figure 3. Axial Fuel Assembly Arrangement
(Ref. 1 Figure 4.2-2, in inches)

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	521.95 kg

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

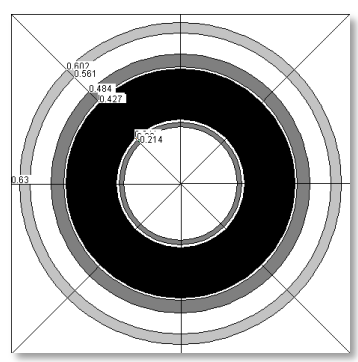
- The nozzle and core plate materials, heights, and axial locations are obtained from Ref. 1.
- The lower core plate thickness is obtained from Reference 9 for a generic Westinghouse plant.
- The upper core plate thickness is assumed. The model should be insensitive to this value.
- The nozzle masses are assumed to be equal, with a total mass 12.5 kgs. The reference for this value has been misplaced. 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 coolant flow holes. 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) 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. 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	0.00624 g/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, assuming natural 19.8 at%, of B_2O_3-SiO_2 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.

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

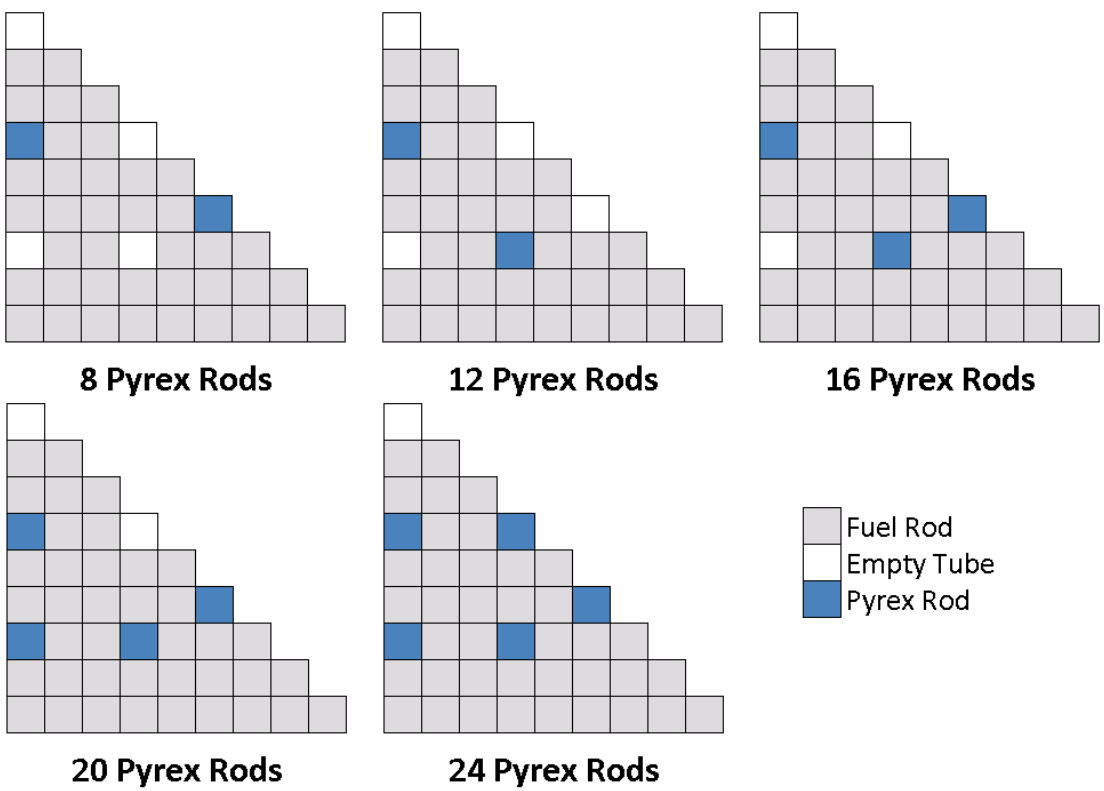


Figure 4. Pyrex Configurations (Octant Symmetry)
(Ref. 1 Figure 4.3-4)

1.6 CONTROL ROD GEOMETRY

WBN1 utilized hybrid B_4C RCCAs with AIC tips. These rods are inserted into each guide tube of any assembly in a controlled 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.

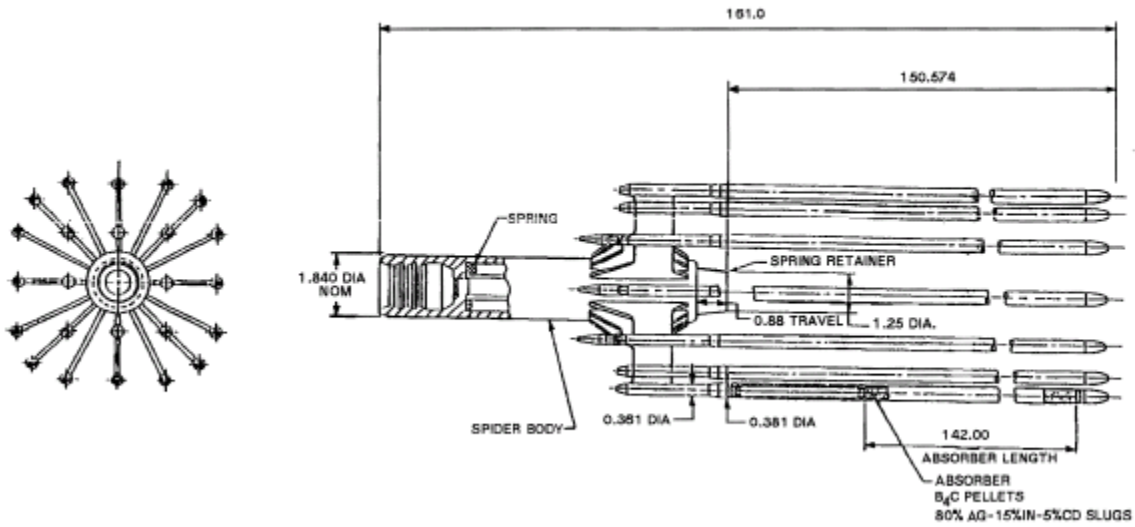
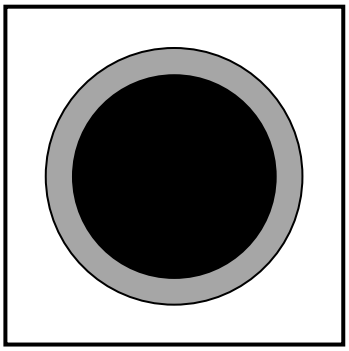


Figure 5. RCCA Assembly
(Ref. 1 Figure 4.2-15, in inches)

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 (fully inserted)	17.031 cm	
Plenum Height above Poison	10.7 cm	
End Plug Height	≈ 1.9 cm	
Step Size	1.5875 cm	
Maximum 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

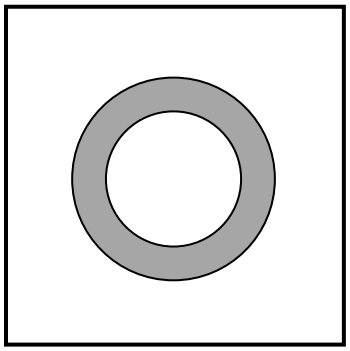
Input	Value
Material	SS304
Outer Radius	0.538 cm
Height	11.0 cm
Plenum Height	22.2 cm
Axial Location	383.31 cm
End Plug Height	≈ 2.54 cm

1.8 INSTRUMENT THIMBLE GEOMETRY

Instrument tube thimbles are sometimes 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 pressure boundaries and displace 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.

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 11: 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

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 3D problems the corrected pellet density is the following, based on total assembly fuel mass:

$$1150.7\ \frac{lbs}{assy} \times \frac{1000\ g}{2.2\ lbs} \times \frac{assy}{264\ rods} \times \frac{rod}{\pi \times (0.3225/2\ in)^2 \times 144\ in} \times \frac{in^3}{2.54^3\ cm^3} = \mathbf{10.257\ g/cc}$$

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**.

PROBLEMS

Problem #1: 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.

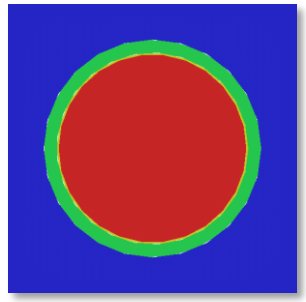


Figure P1-1: Problem 1 KENO-VI Geometry

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 four calculations. The first (part A) represents typical zero power isothermal conditions which are representative of power reactor startup physics testing. The other calculations (parts 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. 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	

†Clad temperature set at moderator temperature

Table P1-2: Problem 1 Input Specification

Input	Value	Section
Fuel Density	10.36 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 moderator densities correspond to the input temperature and core pressure conditions (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:

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

REFERENCE SOLUTION

The reference values for this benchmark problem are calculated by the SCALE 6.1 (Ref. 6) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). KENO-VI input 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. Unfortunately, this solution is only available at certain temperatures (without some significant pre-processing), so a small adjustment to the reference value is made based on multi-group (MG) results. This calculation is documented below.

Cross Sections

The reference solution is based on ENDF/B-VII CE cross sections as obtained from the SCALE 6.1 component CENTRM (**ce-v7-endf**) (Ref. 6).

Materials

The SCALE 6.1 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 CE material temperatures are set to either 600K, 900K, or 1200K, to coincide with the availability of the CE cross section data. Unlike MG calculations, there is no ability to interpolate on temperature. A small correction for this limitation is provided in a subsequent

section of this document. In the future, temperature specific CE libraries can be developed to better address this limitation.

- The fuel isotopes are calculated based on the equations in Table 11 (and Ref. 5) and are provided here.

Table P1-3: Problem 1 Calculated 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 will be 40^6. This limits the standard deviation in the resulting k-effective to approximately 10 pcm (actual uncertainties will be provided in the results).

Geometry

The pin cell geometry will be modeled explicitly with concentric fuel, gap, and cladding cylinders using the radii provided in Table 1. Reflective boundary conditions are applied on all sides.

Input File - #1A

```
=csas6
casl vera benchmark problem #1a
ce_v7_endf
read composition
uo2    1 den=10.36     1.0    600.0   92234 0.0179
                                       92235 3.1
                                       92236 0.0143
                                       92238 96.8678 end

 he     2 den=0.0001786 1.0    600.0 end
 zirc4  3 den=6.56      1.0    600.0 end
 h2o    4 den=0.743     0.9987 600.0 end
 boron  4 den=0.743     0.0013 600.0 end
end composition

read parameter
 gen=2000
 npg=20000
 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
```

Computer Code

The reference calculations were executed with SCALE 6.1 on cpile2.ornl.gov using the following standard run script:

/scale/scale6.1/cmds/batch6.1

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	1A Atom Density (/barn-cm)	1B, 1C, 1D Atom Density (/barn-cm)
Fuel	92234	4.20622E-06	→
	92235	7.25342E-04	→
	92236	3.33174E-06	→
	92238	2.23790E-02	→
	8016	4.62237E-02	→
Gap	2004	2.68714E-05	→
Cladding	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	8016	2.48112E-02	2.20729E-02
	1001	4.96224E-02	4.41459E-02
	5010	1.07070E-05	9.52537E-06
	5011	4.30971E-05	3.83408E-05

Temperature Correction (problem 1A only)

It's difficult to precisely model actual reactor conditions with CE cross sections without the ability to interpolate on temperature. There are CE libraries at 600K, 900K, and 1200K, but currently no method of performing calculations at intermediate temperatures. Ideally, a temperature-specific CE library could be created for HZP isothermal conditions. In the mean time, we can correct the reference CE result with a reactivity worth of the temperature difference calculated from multi-group (MG) models. This is expected to introduce only a small error to the reference result at 565K, as the worth of the 35 K difference is less than approximately 150 pcm.

In order to achieve the most accuracy as possible, the temperature correction is calculated with KENO-VI using the largest MG library currently available. This library contains 999 groups and is not included with the standard SCALE distribution package. Its details are provided below.

999g ENDF/B-VII Library	/home/dw8/1000/999/v7_999_vitaminb6
Date	October 1, 2009
Checksum	3073493320

Using this 999g MG library, KENO-VI calculated eigenvalues at the CE library temperature and 565K. The worth of the isothermal temperature difference is calculated as an eigenvalue difference in the table below.

Table P1-5: 999g Temperature Correction Results

Isothermal Temperature	k-effective
600 K	1.18366 ± 0.00009
565 K	1.18490 ± 0.00009
Diff	**0.00124 ± 0.00012**

REFERENCE SOLUTION RESULTS

Note that it has been found after the fact that U-234 and U-238 isotopics were slightly off in the input files (highlighted in red above). This is expected to only make a 80 pcm difference in reactivity.

The eigenvalue calculated by CE KENO-VI for problem 1A (at 600K) is **1.18575 ± 0.00011**. For the results in Table P1-6, this value is corrected for the temperature difference as described in the previous section. Note that this is a temperature only correction, and does not include density effects (since the correct density can be explicitly specified in the input).

The following table contains the results from the CE KENO-VI calculations at 600K.

Table P1-6: Problem 2 Reference Solution Results

Problem	Moderator Temperature	Fuel Temperature	Moderator Density	k-effective
1A	565 K	565 K	0.743 g/cc	**1.18699 ± 0.00017**
1B	600 K	600 K	0.661 g/cc	**1.18221 ± 0.00011**
1C		900 K		**1.17163 ± 0.00010**
1D		1200K		**1.16226 ± 0.00011**

Problem #2: 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.

SPECIFICATIONS

The problem consists of a single Westinghouse 17x17-type fuel lattice at beginning-of-life (BOL) as depicted in Figure 2. 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), and Pyrex (borosilicate glass - B_2O_3-SiO_2) are used for neutron poisons inserted into the guide tubes (Sections 1.5 and 1.6), and stainless steel 304 is used for the instrument tube thimble (Section 1.8) and other structural materials.

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. Finally, parts 2E to 2J test the capability to accurately model poisons in the control rod guide tubes and the presence of the instrument tube thimble tube. Input specifications are provided below in Tables 2-1, 2-2, and 2-3.

Table P2-1: Problem 2 Calculations

Problem	Moderator Temperature†	Fuel Temperature	Moderator Density	Inserts
2A	565 K	565 K	0.743 g/cc	None
2B	600 K	600 K	0.661 g/cc	
2C		900 K		
2D		1200 K		
2E		600 K	0.743 g/cc	12 Pyrex rods
2F				24 Pyrex rods
2G				24 AIC rods
2H				24 B_4C rods
2I				Instrument Thimble
2J				Instrument Thimble + 24 Pyrex rods

†Clad temperature set at moderator temperature

Table P2-2: Problem 2 Input Specification

Input	Value	Section
Fuel Density	10.36 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 moderator densities correspond to the input temperature and core pressure conditions (Reference 4).
- 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 lattice layouts for the ten problems are provided in Figure P2-1 below.

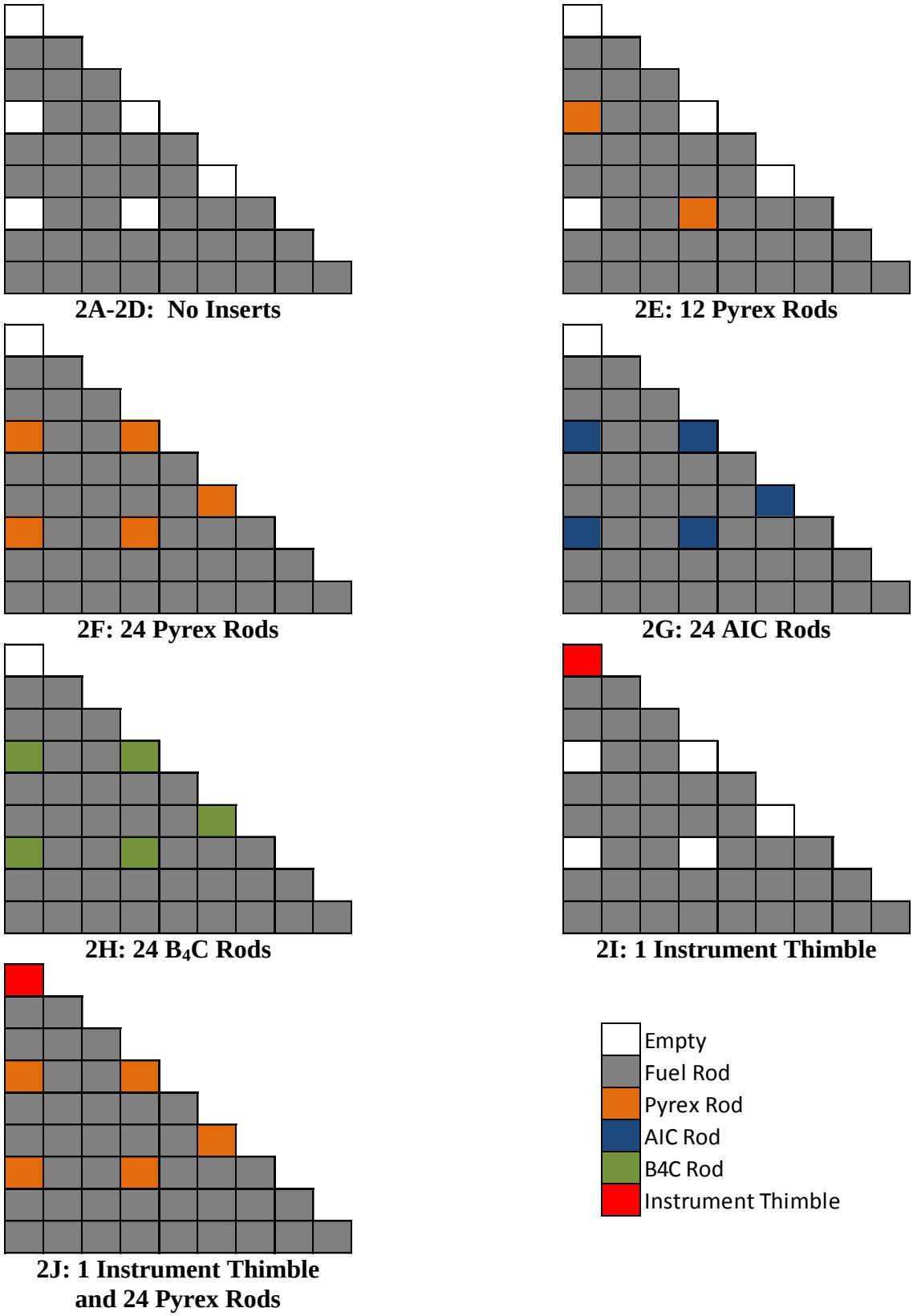


Figure P2-1: Problem 2 Lattice Layouts (Octant Symmetry)

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 symmetry
- Account for effects of prompt and delayed gammas on pin powers
- Output pin-by-pin relative reaction rates / power
- Provide 2g 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 SCALE 6.1 (Ref. 6) code KENO-VI, a continuous energy (CE) Monte Carlo-based transport tool (Ref. 7). 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 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 (without some significant pre-processing), so a small adjustment to the reference eigenvalue (not pin powers) is made based on multi-group (MG) results. This calculation is documented below.

Cross Sections

The reference solution is based on ENDF/B-VII CE cross sections as obtained from the SCALE 6.1 component CENTRM (**ce-v7-endf**) (Ref. 6).

Materials

The SCALE 6.1 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 CE material temperatures are set to either 600K, 900K, or 1200K, to coincide with the availability of the CE cross section data. Unlike MG calculations, there is no ability to interpolate on temperature. A small correction for this limitation is provided in a subsequent section of this document. In the future, temperature specific CE libraries can be developed to better address this limitation.
- The fuel isotopes are calculated based on the equations in Table 11 (and Ref. 5) and are provided here.

Table P2-3: Problem 2 Calculated 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 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 SCALE 6.1 built-in material for Pyrex is used, which results in a slight difference in isotopics from the values provided in Section 1.5. The actual reference isotopics are provided below.

Parameters

In order to get the power distribution uncertainty as low as possible, given the practical limitations of a single core calculation, a large number of particles much be used. In this case, 100^6 particles are used, skipping 400 generations. This resulted in an eigenvalue uncertainty of less than **9 pcm** and a maximum power distribution uncertainty of **0.11%**.

Geometry

The pin cell geometry will be modeled explicitly with concentric fuel, gap, and cladding cylinders using the radii provided in Table 1. The lattice is modeled according to Section 1.2 in quarter symmetry, including the assembly gaps. Reflective boundary conditions are applied on all sides.

Input File - #2A (eigenvalue only)

```
=csas6
casl vera benchmark problem #2a
ce_v7_endf
read composition
 uo2     1 den=10.36     1.0    600.0  92234 0.0179
                                       92235 3.1
                                       92236 0.0143
                                       92238 96.8678 end
 he      2 den=0.0001786 1.0    600.0 end
 zirc4   3 den=6.56      1.0    600.0 end
 h2o     4 den=0.743     0.9987 600.0 end
 boron   4 den=0.743     0.0013 600.0 end
end composition

read parameter
 gen=2000
 npg=20000
 nsk=200
 htm=no
end parameter

read geometry
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  4p0.630  2p0.5
 media 1 1 1
 media 2 1 2 -1
 media 3 1 3 -2
 media 4 1 4 -3
 boundary 4

unit 10
 com='fuel rod - north'
 cylinder 1    0.4096         2p0.5 chord -y=0
 cylinder 2    0.418          2p0.5 chord -y=0
 cylinder 3    0.475          2p0.5 chord -y=0
 cuboid   4  2p0.630 0 -0.630 2p0.5
 media 1 1 1
 media 2 1 2 -1
 media 3 1 3 -2
 media 4 1 4 -3
 boundary 4

unit 11
 com='fuel rod - west'
 cylinder 1  0.4096          2p0.5 chord +x=0
 cylinder 2  0.418           2p0.5 chord +x=0
 cylinder 3  0.475           2p0.5 chord +x=0
 cuboid   4  0.630 0 2p0.630 2p0.5
 media 1 1 1
 media 2 1 2 -1
 media 3 1 3 -2
 media 4 1 4 -3
 boundary 4
```

```
unit 2
 com='guide tube'
 cylinder 1    0.561 2p0.5
 cylinder 2    0.602 2p0.5
 cuboid   3  4p0.630 2p0.5
 media 4 1 1
 media 3 1 2 -1
 media 4 1 3 -2
 boundary 3

unit 20
 com='guide tube - north'
 cylinder 1    0.561          2p0.5 chord -y=0
 cylinder 2    0.602          2p0.5 chord -y=0
 cuboid   3  2p0.630 0 -0.630 2p0.5
 media 4 1 1
 media 3 1 2 -1
 media 4 1 3 -2
 boundary 3

unit 21
 com='guide tube - west'
 cylinder 1  0.561           2p0.5 chord +x=0
 cylinder 2  0.602           2p0.5 chord +x=0
 cuboid   3  0.630 0 2p0.630 2p0.5
 media 4 1 1
 media 3 1 2 -1
 media 4 1 3 -2
 boundary 3

unit 22
 com='guide tube - center'
 cylinder 1  0.561            2p0.5 chord +x=0 chord -y=0
 cylinder 2  0.602            2p0.5 chord +x=0 chord -y=0
 cuboid   3  0.630 0 0 -0.630 2p0.5
 media 4 1 1
 media 3 1 2 -1
 media 4 1 3 -2
 boundary 3

global unit 3
 com='assembly'
 cuboid 1  10.71 0 0 -10.71 2p0.5
 cuboid 2  10.75 0 0 -10.75 2p0.5
 media 4 1 2 -1
 array 1 1 place 1 9 1 0 0 0
 boundary 2

end geometry
read array
 ara=1 nux=9 nuy=9 nuz=1 typ=square gbl=1
 com='pin layout'
 fill
   11  1  1  1  1  1  1  1  1
   11  1  1  1  1  1  1  1  1
   21  1  1  2  1  1  1  1  1
   11  1  1  1  1  2  1  1  1
   11  1  1  1  1  1  1  1  1
   21  1  1  2  1  1  2  1  1
   11  1  1  1  1  1  1  1  1
```

```
   11  1  1  1  1  1  1  1  1
   22 10 10 20 10 10 20 10 10 end fill
end array
read bnds
   body=2
   all=mirror
end bnds
end data
end
```

Computer Code

The reference calculations were executed with SCALE 6.1 on cpile2.ornl.gov using the following standard run script:

/scale/scale6.1/cmds/batch6.1

These calculations ran on a single processor for approximately nine 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	2A,2E-2J Atom Density (/barn-cm)	2B, 2C, 2D Atom Density (/barn-cm)
Fuel	92234	4.20622E-06	→
	92235	7.25342E-04	→
	92236	3.33174E-06	→
	92238	2.23790E-02	→
	8016	4.62237E-02	→
Gap	2004	2.68714E-05	→
Cladding	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	8016	2.48112E-02	2.20729E-02
	1001	4.96224E-02	4.41459E-02
	5010	1.07070E-05	9.52537E-06
	5011	4.30971E-05	3.83408E-05
Pyrex	8016	4.53216E-02	n/a
	5010	9.22829E-04	n/a
	5011	3.71450E-03	n/a
	13027	5.02189E-04	n/a
	14028	1.67738E-02	n/a
	14029	8.52123E-04	n/a
	14030	5.62383E-04	n/a
	11023	2.41648E-03	n/a
SS304	26054	3.48029E-03	n/a
	26056	5.41037E-02	n/a
	26057	1.23875E-03	n/a
	26058	1.65166E-04	n/a
	24050	7.64915E-04	n/a
	24052	1.47508E-02	n/a
	24053	1.67243E-03	n/a
	24054	4.16346E-04	n/a
	14028	1.58197E-03	n/a
	14029	8.03653E-05	n/a
	14030	5.30394E-05	n/a
	6000	3.20895E-04	n/a
	15031	6.99938E-05	n/a
	25055	1.75387E-03	n/a
	28058	5.32410E-03	n/a
	28060	2.03543E-03	n/a
	28061	8.81241E-05	n/a
	28062	2.79969E-04	n/a
	28064	7.09672E-05	n/a
AIC	47107	2.36159E-02	n/a
	47109	2.19403E-02	n/a
	49113	3.44262E-04	n/a
	49115	7.68050E-03	n/a
	48106	3.41523E-05	n/a
	48108	2.43165E-05	n/a
	48110	3.41250E-04	n/a
	48111	3.49720E-04	n/a
	48112	6.59276E-04	n/a
	48113	3.33873E-04	n/a
	48114	7.84957E-04	n/a
	48116	2.04641E-04	n/a
B_4C	5010	1.52689E-02	n/a
	5011	6.14591E-02	n/a
	6000	1.91820E-02	n/a

Temperature Correction (problem 2A only)

It's difficult to precisely model actual reactor conditions with CE cross sections without the ability to interpolate on temperature. There are CE libraries at 600K, 900K, and 1200K, but currently no method of performing calculations at intermediate temperatures. Ideally, a temperature-specific CE library could be created for HZP isothermal conditions. In the meantime, we can correct the reference CE result with a reactivity worth of the temperature difference calculated from multi-group (MG) models. This is expected to introduce only a small error to the reference result at 565K, as the worth of the 35 K difference is less than approximately 150 pcm.

In order to achieve the most accuracy as possible, the temperature correction is calculated with KENO-VI using the largest MG library currently available. This library contains 999 groups and is not included with the standard SCALE distribution package. Its details are provided below.

999g ENDF/B-VII Library	/home/dw8/1000/999/v7_999_vitaminb6
Date	October 1, 2009
Checksum	3073493320

Using this 999g MG library, KENO-VI calculated eigenvalues at the CE library temperature and 565K. The worth of the isothermal temperature difference is calculated as an eigenvalue difference in the table below.

Table P2-5: 999g Temperature Correction Results

Isothermal Temperature	k-effective
600 K	1.180364 ± 0.000092
565 K	1.181315 ± 0.000091
Diff	**0.000951 ± 0.000129**

REFERENCE SOLUTION RESULTS

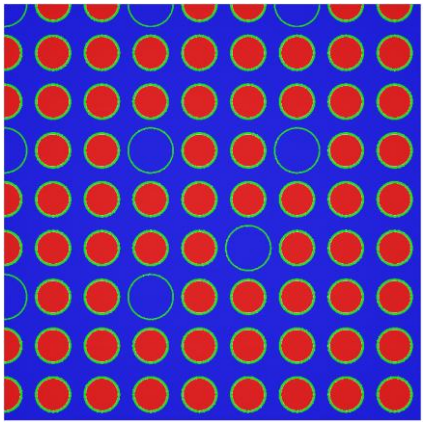
Note that it has been found after the fact that U-234 and U-238 isotopics were slightly off in all the input files for problem 2 (highlighted in red above). This is expected to only make an 80 pcm difference in reactivity.

The eigenvalue calculated by CE KENO-VI for problem 2A (at 600K) is **1.18144 ± 0.00012**. For the results in Table P2-6, this value is corrected for the temperature difference as described in the previous section. Note that this is a temperature only correction, and does not include density effects (since the correct density can be explicitly specified in the input).

The following table contains the results from the CE KENO-VI calculations at 600K.

Table P2-6: Problem 2 Reference Solution Eigenvalue Results

Problem	Fuel Temperature	Moderator Density	Inserts	k-effective
2A	565 K	0.743 g/cc	None	**1.18239 ± 0.00018**
2B	600 K	0.661 g/cc		**1.18386 ± 0.00012**
2C	900 K			**1.17403 ± 0.00011**
2D	1200 K			**1.16601 ± 0.00012**
2E	600 K	0.743 g/cc	12 Pyrex rods	**1.07251 ± 0.00013**
2F			24 Pyrex rods	**0.98047 ± 0.00013**
2G			24 AIC rods	**0.84695 ± 0.00012**
2H			24 B_4C rods	**0.78746 ± 0.00013**
2I			Instrument Thimble	**1.18061 ± 0.00012**
2J			Instrument Thimble + 24 Pyrex rods	**0.97941 ± 0.00012**



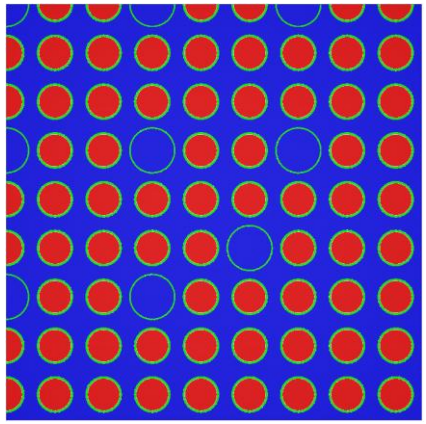
1.03765	1.01085							
1.03529	1.01027	1.01144						
	1.03677	1.03588						
1.03441	1.00938	1.00879	1.04413	1.03117				
1.03117	1.00850	1.00909	1.04619	1.04884				
	1.02499	1.02558		1.03500	1.01586	0.97464		
1.01027	0.98877	0.99054	1.01115	0.98318	0.96639	0.94990	0.93989	
0.97523	0.97081	0.97228	0.97552	0.96580	0.95550	0.94873	0.94225	0.94784

Min 0.93989 Max 1.04884 Avg 1.00000

0.092%	0.090%							
0.092%	0.090%	0.090%						
	0.090%	0.090%						
0.092%	0.090%	0.090%	0.090%	0.090%				
0.092%	0.090%	0.090%	0.090%	0.090%				
	0.090%	0.090%		0.090%	0.090%	0.090%		
0.092%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	
0.092%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%

Min 0.090% Max 0.092% Avg 0.090%

Figure P2-2: Problem 2A CE KENO-VI Power Distribution Results



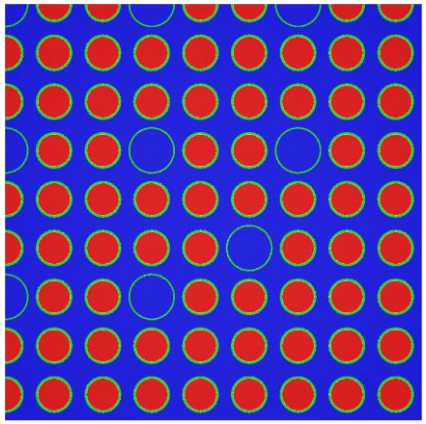
1.03583	1.01174							
1.03701	1.01115	1.01262						
	1.03730	1.03730						
1.03289	1.01027	1.01174	1.04142	1.03084				
1.02907	1.00733	1.01085	1.04200	1.04612				
	1.02378	1.02614		1.03113	1.01379	0.97354		
1.00880	0.98882	0.98940	1.01085	0.98411	0.96648	0.95120	0.94092	
0.97941	0.97471	0.97442	0.97500	0.96707	0.95679	0.94915	0.94180	0.94709

Min 0.94092 Max 1.04612 Avg 1.00000

0.092%	0.090%							
0.092%	0.090%	0.090%						
	0.090%	0.090%						
0.085%	0.090%	0.090%	0.090%	0.090%				
0.092%	0.090%	0.090%	0.090%	0.090%				
	0.090%	0.090%		0.090%	0.090%	0.090%		
0.092%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	
0.092%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%

Min 0.085% Max 0.092% Avg 0.090%

Figure P2-3: Problem 2B CE KENO-VI Power Distribution Results



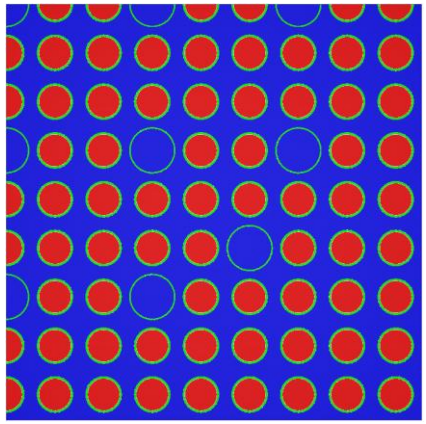
1.03759	1.01359							
1.03551	1.01300	1.01122						
	1.03551	1.03700						
1.03255	1.01033	1.01240	1.04351	1.03077				
1.03107	1.00529	1.00914	1.04262	1.04648				
	1.02366	1.02425		1.03255	1.01418	0.97300		
1.00914	0.98959	0.98959	1.01151	0.98426	0.96589	0.94900	0.94130	
0.97774	0.97389	0.97537	0.97418	0.96707	0.95641	0.94929	0.94367	0.94722

Min 0.94130 Max 1.04648 Avg 1.00000

0.085%	0.090%							
0.085%	0.090%	0.090%						
	0.090%	0.090%						
0.092%	0.090%	0.090%	0.090%	0.090%				
0.092%	0.090%	0.090%	0.090%	0.090%				
	0.090%	0.090%		0.090%	0.090%	0.090%		
0.092%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	
0.092%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%

Min 0.085% Max 0.092% Avg 0.090%

Figure P2-4: Problem 2C CE KENO-VI Power Distribution Results



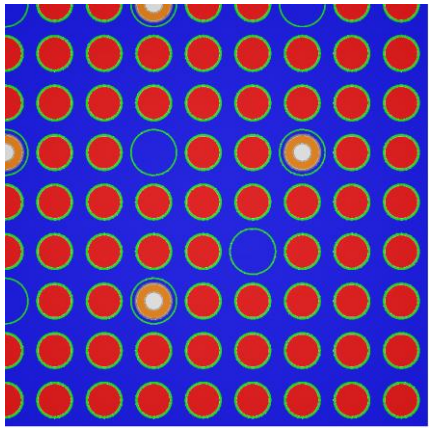
1.03786	1.01190							
1.03607	1.01250	1.01220						
	1.03637	1.03846						
1.03547	1.01071	1.01250	1.04204	1.03279				
1.03010	1.00623	1.00832	1.04174	1.04741				
	1.02443	1.02533		1.03160	1.01488	0.97281		
1.01100	0.98862	0.98833	1.00921	0.98295	0.96505	0.95013	0.94028	
0.98027	0.97549	0.97311	0.97520	0.96624	0.95699	0.94715	0.94446	0.94834

Min 0.94028 Max 1.04741 Avg 1.00000

0.092%	0.090%							
0.085%	0.090%	0.090%						
	0.090%	0.090%						
0.092%	0.090%	0.090%	0.090%	0.090%				
0.092%	0.090%	0.090%	0.090%	0.090%				
	0.090%	0.090%		0.090%	0.090%	0.090%		
0.092%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	
0.092%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%

Min 0.085% Max 0.092% Avg 0.090%

Figure P2-5: Problem 2D CE KENO-VI Power Distribution Results



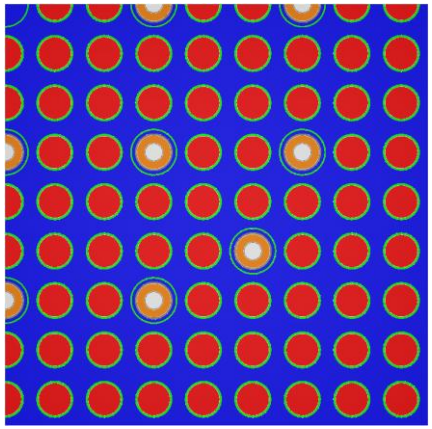
1.02160	0.99435							
0.93403	0.96484	0.99825						
	0.93468	1.02516						
0.93630	0.96841	1.00214	1.03716	1.02938				
1.03003	1.00279	0.97652	0.95349	1.02225				
	1.03619	0.94473		0.95998	1.04203	1.02906		
1.05630	1.02160	0.97717	0.93792	0.97749	1.01284	1.02322	1.02679	
1.03100	1.02192	1.00506	0.99371	1.00376	1.02160	1.02711	1.03846	1.04851

Min 0.93403 Max 1.05630 Avg 1.00000

0.092%	0.100%							
0.099%	0.090%	0.100%						
	0.100%	0.090%						
0.099%	0.100%	0.090%	0.100%	0.090%				
0.092%	0.100%	0.090%	0.100%	0.090%				
	0.090%	0.100%		0.100%	0.090%	0.090%		
0.092%	0.090%	0.100%	0.100%	0.090%	0.090%	0.090%	0.090%	
0.092%	0.100%	0.100%	0.100%	0.090%	0.090%	0.090%	0.090%	0.090%

Min 0.090% Max 0.100% Avg 0.094%

Figure P2-6: Problem 2E CE KENO-VI Power Distribution Results



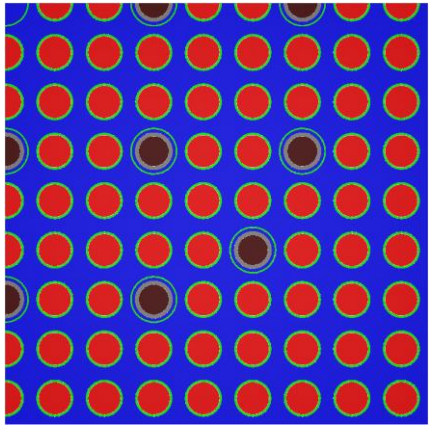
1.07808	1.04259							
0.97304	0.99078	0.97482						
	0.93684	0.92939						
0.92584	0.95920	0.95494	0.91449	0.93010				
0.93081	0.96204	0.96062	0.91449	0.91165				
	0.94465	0.94288		0.93613	0.96701	1.03372		
0.97588	1.00498	1.00675	0.98085	1.01917	1.04756	1.07808	1.10541	
1.04579	1.05076	1.05253	1.05253	1.06885	1.09121	1.11002	1.12883	1.14941

Min 0.91165 Max 1.14941 Avg 1.00000

0.092%	0.100%							
0.099%	0.100%	0.100%						
	0.100%	0.100%						
0.099%	0.100%	0.100%	0.100%	0.100%				
0.106%	0.100%	0.100%	0.100%	0.100%				
	0.100%	0.100%		0.100%	0.100%	0.100%		
0.099%	0.100%	0.100%	0.100%	0.100%	0.100%	0.100%	0.090%	
0.092%	0.100%	0.100%	0.090%	0.100%	0.090%	0.090%	0.090%	0.090%

Min 0.090% Max 0.106% Avg 0.098%

Figure P2-7: Problem 2F CE KENO-VI Power Distribution Results



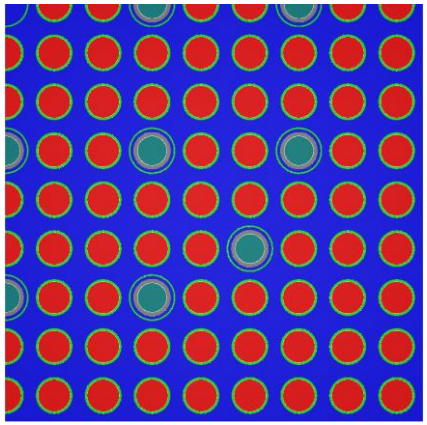
1.07312	1.03534							
0.93924	0.96429	0.94088						
	0.88503	0.87640						
0.87312	0.91994	0.91419	0.85340	0.87230				
0.87928	0.92568	0.92117	0.85587	0.85258				
	0.90761	0.90926		0.90761	0.96552	1.07189		
0.96347	1.00659	1.00905	0.97825	1.03780	1.09407	1.15238	1.20084	
1.06984	1.07928	1.08462	1.08955	1.11994	1.15936	1.20167	1.23616	1.26614

Min 0.85258 Max 1.26614 Avg 1.00000

0.099%	0.100%							
0.106%	0.110%	0.110%						
	0.110%	0.110%						
0.113%	0.110%	0.110%	0.110%	0.110%				
0.113%	0.110%	0.110%	0.110%	0.110%				
	0.110%	0.110%		0.110%	0.100%	0.100%		
0.106%	0.100%	0.100%	0.110%	0.100%	0.100%	0.100%	0.100%	
0.099%	0.100%	0.100%	0.100%	0.100%	0.100%	0.100%	0.090%	0.090%

Min 0.090% Max 0.113% Avg 0.105%

Figure P2-8: Problem 2G CE KENO-VI Power Distribution Results



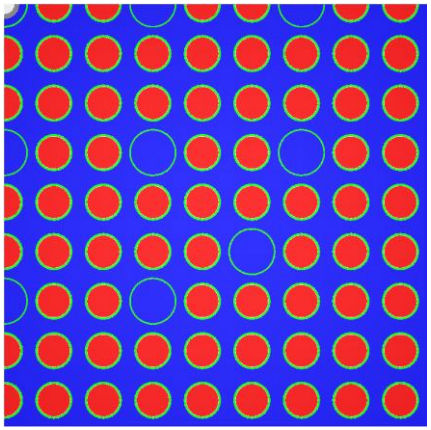
1.06435	1.02150							
0.92297	0.94815	0.91988						
	0.86244	0.85581						
0.85581	0.89823	0.89381	0.82753	0.85095				
0.85670	0.90883	0.90044	0.83593	0.83416				
	0.89558	0.89602		0.90353	0.97245	1.09086		
0.96052	1.00603	1.00912	0.97952	1.04933	1.11516	1.18541	1.24373	
1.07805	1.08512	1.09395	1.10235	1.13769	1.18718	1.23976	1.28482	1.31796

Min 0.82753 Max 1.31796 Avg 1.00000

0.106%	0.110%							
0.113%	0.110%	0.110%						
	0.120%	0.120%						
0.120%	0.110%	0.110%	0.120%	0.120%				
0.113%	0.110%	0.110%	0.120%	0.120%				
	0.110%	0.110%		0.110%	0.110%	0.100%		
0.113%	0.110%	0.110%	0.110%	0.110%	0.100%	0.100%	0.100%	
0.106%	0.110%	0.110%	0.110%	0.100%	0.100%	0.100%	0.100%	0.090%

Min 0.090% Max 0.120% Avg 0.110%

Figure P2-9: Problem 2H CE KENO-VI Power Distribution Results



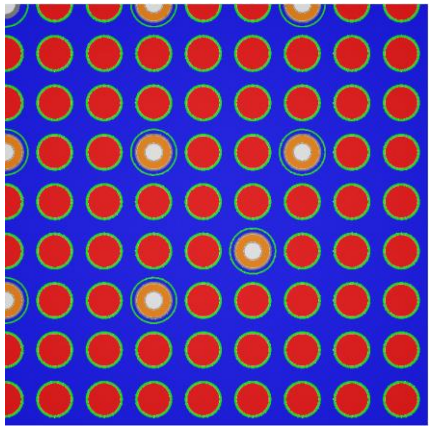
1.00503	0.99206							
1.02654	1.00355	1.00709						
	1.03184	1.03921						
1.03272	1.00768	1.01239	1.04569	1.03243				
1.03243	1.00621	1.01033	1.04421	1.05246				
	1.02654	1.02801		1.03773	1.01976	0.97645		
1.01210	0.99000	0.99177	1.01298	0.98470	0.96702	0.95111	0.94138	
0.97880	0.97321	0.97409	0.97792	0.96908	0.95641	0.94875	0.94521	0.94728

Min 0.94138 Max 1.05246 Avg 1.00000

0.092%	0.090%							
0.092%	0.090%	0.090%						
	0.090%	0.090%						
0.092%	0.090%	0.090%	0.090%	0.090%				
0.092%	0.090%	0.090%	0.090%	0.090%				
	0.090%	0.090%		0.090%	0.090%	0.090%		
0.092%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	
0.092%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%	0.090%

Min 0.090% Max 0.092% Avg 0.090%

Figure P2-10: Problem 2I CE KENO-VI Power Distribution Results



1.03953	1.02106							
0.96069	0.98235	0.97170						
	0.93192	0.92659						
0.93014	0.95998	0.95571	0.91700	0.93085				
0.93156	0.96211	0.95855	0.91594	0.91239				
	0.94541	0.94364		0.94009	0.97063	1.03527		
0.97631	1.00757	1.00792	0.98093	1.02142	1.05018	1.08215	1.10914	
1.04770	1.05445	1.05551	1.05764	1.07256	1.09138	1.11163	1.13151	1.15176

Min 0.91239 Max 1.15176 Avg 1.00000

0.099%	0.100%							
0.099%	0.100%	0.100%						
	0.100%	0.100%						
0.099%	0.100%	0.100%	0.100%	0.100%				
0.106%	0.100%	0.100%	0.100%	0.100%				
	0.100%	0.100%		0.100%	0.100%	0.100%		
0.099%	0.100%	0.100%	0.100%	0.100%	0.100%	0.090%	0.100%	
0.099%	0.090%	0.100%	0.100%	0.100%	0.090%	0.090%	0.090%	0.090%

Min 0.090% Max 0.106% Avg 0.098%

Figure P2-11: Problem 2J 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 problem does not include guide tube inserts such as RCCAs or discrete burnable poisons. However, 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-re-entrant boundaries (vacuum). Radially, the assembly can be treated in quarter symmetry with reflection as was done for Problem 2.

Table P3-1: Problem 3 Input Specification

Input	Value	Section
Fuel Density	10.257 g/cc	2.2
Fuel Enrichment	3.1%	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 enrichment is the maximum 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).
- 600K is used for coolant and cladding temperatures rather than 565K to be consistent with available CE cross section libraries.

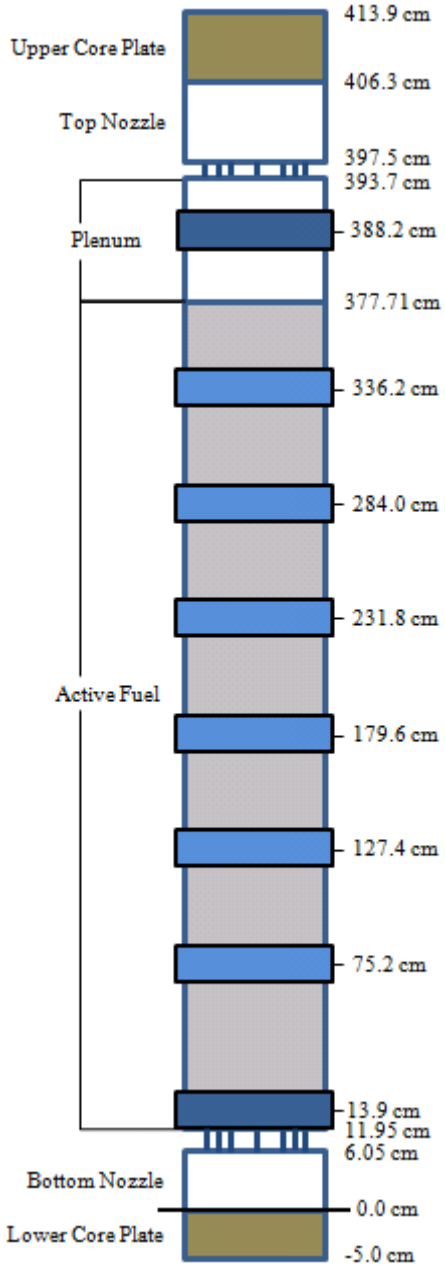


Figure P3-1: Problem 3 Axial Geometry (without plugs)

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 was used exclusively for this case. 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.

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).

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 11 (and Ref. 5) and are provided here.

Table P3-2: Problem 3 Calculated 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.

- 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.

Parameters

A very large number of particle histories is needed to get the power distribution uncertainty low. In this case $4.4e^9$ produces less than 2 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.

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

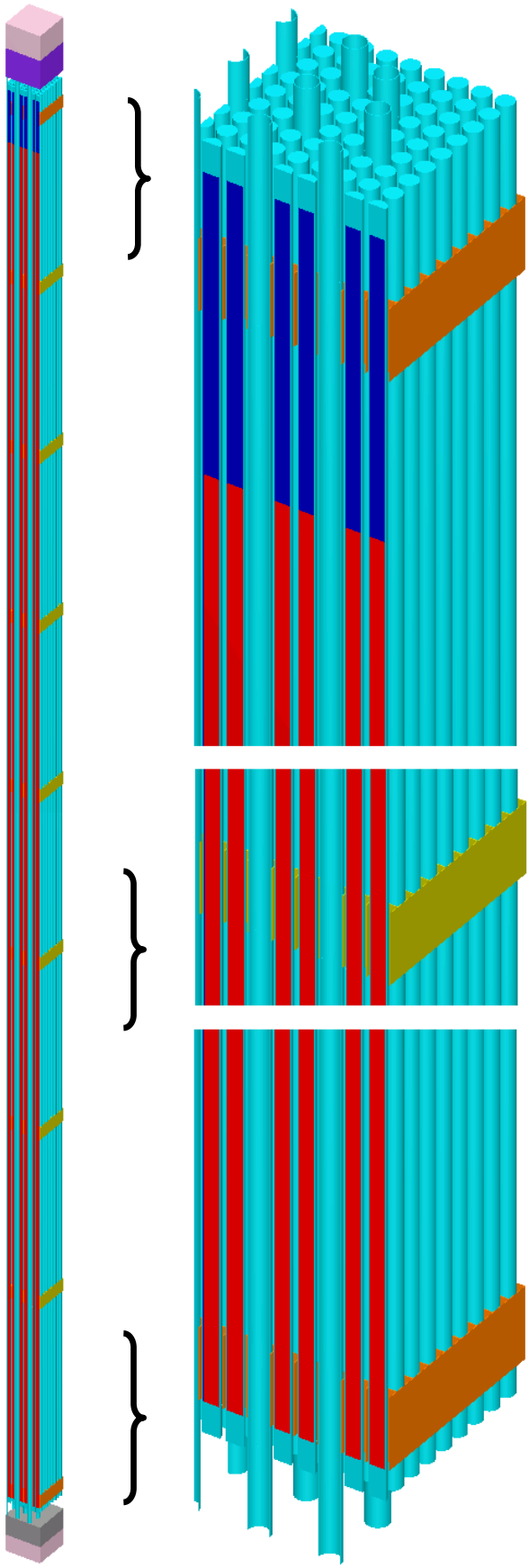


Figure P3-2: Problem 3 Reference Model

Input File

The input for this problem is over 54,000 lines long, so it is excluded from this document.

Computer Code

The reference calculations were executed with SCALE 6.2 (scale_dev) on cpile2.ornl.gov using a custom PBS script provided by the code developer.

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	3A Atom Density (/barn-cm)
Fuel	92235	7.18132E-04
	92236	3.29861E-06
	92234	6.11864E-06
	8016	4.57642E-02
	92238	2.21546E-02
Gap	2004	2.68714E-05
Cladding & Int Grids	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	8016	2.48112E-02
	1001	4.96224E-02
	5010	1.07070E-05
	5011	4.30971E-05
	24053	1.35184E-03
Inconel	22049	1.39360E-04
	22050	1.33435E-04
	22048	1.89901E-03

	24052	1.19218E-02
	24050	6.18222E-04
	26057	1.31002E-04
	26056	5.67247E-03
	26058	1.74340E-05
	24054	3.36501E-04
	26054	3.61353E-04
	28061	6.99255E-04
	28062	2.22953E-03
	28060	1.60862E-02
	28058	4.17608E-02
	28064	5.67796E-04
	22046	2.12518E-04
	14030	1.35748E-04
	22047	1.91652E-04
	14028	4.04885E-03
	14029	2.05685E-04
	24053	3.19881E-04
Top Nozzle	14030	1.01436E-05
	15031	1.33861E-05
	14029	1.53696E-05
	24052	2.82102E-03
	24050	1.46288E-04
	26057	2.39045E-04
	26056	1.03508E-02
	26058	3.18125E-05
	25055	3.35423E-04
	24054	7.96251E-05
	26054	6.59376E-04
	28060	3.91071E-04
	28061	1.69996E-05
	1001	4.00685E-02
	28064	1.38037E-05
	28058	1.01525E-03
	28062	5.42021E-05
	6000	6.13703E-05
	5011	3.80151E-05
	14028	3.02547E-04
	8016	2.00342E-02
	5010	9.44445E-06
	24053	4.67133E-04
Bottom Nozzle	14030	1.48131E-05
	15031	1.95482E-05
	14029	2.24448E-05
	24052	4.11963E-03
	24050	2.13630E-04
	26057	3.49086E-04
	26056	1.51156E-02
	26058	4.64569E-05
	25055	4.89830E-04
	24054	1.16279E-04
	26054	9.62909E-04
	28060	5.71094E-04

	28061	2.48251E-05
	1001	3.57697E-02
	28064	2.01580E-05
	28058	1.48260E-03
	28062	7.91532E-05
	6000	8.96212E-05
	5011	3.70781E-05
	14028	4.41821E-04
	8016	1.78849E-02
	5010	9.21166E-06
	24053	8.35998E-04
Core Plates	14030	2.65101E-05
	15031	3.49842E-05
	14029	4.01681E-05
	24052	7.37264E-03
	24050	3.82319E-04
	26057	6.24736E-04
	26056	2.70514E-02
	26058	8.31409E-05
	25055	8.76618E-04
	24054	2.08098E-04
	26054	1.72326E-03
	28058	2.65331E-03
	28060	1.02205E-03
	1001	2.48109E-02
	28062	1.41655E-04
	28064	3.60754E-05
	28061	4.44278E-05
	6000	1.60389E-04
	5011	1.94983E-05
	14028	7.90698E-04
	8016	1.24055E-02
	5010	4.84416E-06

REFERENCE SOLUTION RESULTS

The eigenvalue calculated by CE KENO-VI for problem 3A (at 600K) is **1.175926 ± 0.000011**.

The 1D axial powers are in Table P3-4 and shown in Figure P3-3.

The 2D radial powers (axially integrated) are provides in Figure P3-4.

The 3D powers are are not provided here but are visualized in Figure P3-5

Table P3-4: Problem 3 Axial Powers

Level	dz	Ubound	Power	Unc
49	7.9274	365.7600	0.17199	0.00030
48	7.9274	357.8326	0.24982	0.00036
47	7.9274	349.9052	0.34741	0.00043
46	7.9274	341.9778	0.44324	0.00048
45	7.9274	334.0504	0.53188	0.00053
44	3.8100	326.1230	0.57023	0.00078
43	8.0645	322.3130	0.66694	0.00059
42	8.0645	314.2485	0.76152	0.00064
41	8.0645	306.1840	0.84664	0.00065
40	8.0645	298.1195	0.92784	0.00071
39	8.0645	290.0550	1.00635	0.00071
38	8.0645	281.9905	1.06980	0.00074
37	3.8100	273.9261	1.06535	0.00106
36	8.0645	270.1161	1.16824	0.00079
35	8.0645	262.0516	1.23924	0.00079
34	8.0645	253.9871	1.29396	0.00080
33	8.0645	245.9226	1.34354	0.00082
32	8.0645	237.8581	1.38768	0.00085
31	8.0645	229.7936	1.41238	0.00086
30	3.8100	221.7291	1.36575	0.00120
29	8.0645	217.9191	1.45563	0.00089
28	8.0645	209.8546	1.49094	0.00090
27	8.0645	201.7901	1.50547	0.00090
26	8.0645	193.7256	1.51386	0.00090
25	8.0645	185.6611	1.51635	0.00089
24	8.0645	177.5966	1.49805	0.00090
23	3.8100	169.5321	1.41733	0.00122
22	8.0645	165.7221	1.47902	0.00090
21	8.0645	157.6576	1.47148	0.00090
20	8.0645	149.5931	1.44353	0.00088
19	8.0645	141.5286	1.40992	0.00086
18	8.0645	133.4641	1.37021	0.00084
17	8.0645	125.3996	1.31205	0.00081
16	3.8100	117.3351	1.21251	0.00112
15	8.0645	113.5251	1.23462	0.00079
14	8.0645	105.4606	1.18611	0.00079
13	8.0645	97.3962	1.12031	0.00077
12	8.0645	89.3317	1.05084	0.00073
11	8.0645	81.2672	0.97653	0.00071
10	8.0645	73.2027	0.88980	0.00068
9	3.8100	65.1382	0.78876	0.00091
8	8.2089	61.3282	0.76646	0.00063
7	8.2089	53.1193	0.68420	0.00059
6	8.2089	44.9104	0.59130	0.00055
5	8.2089	36.7015	0.49576	0.00050
4	8.2089	28.4926	0.39799	0.00045
3	8.2089	20.2837	0.29803	0.00039
2	8.2089	12.0748	0.19619	0.00031
1	3.8659	3.8659	0.13858	0.00038

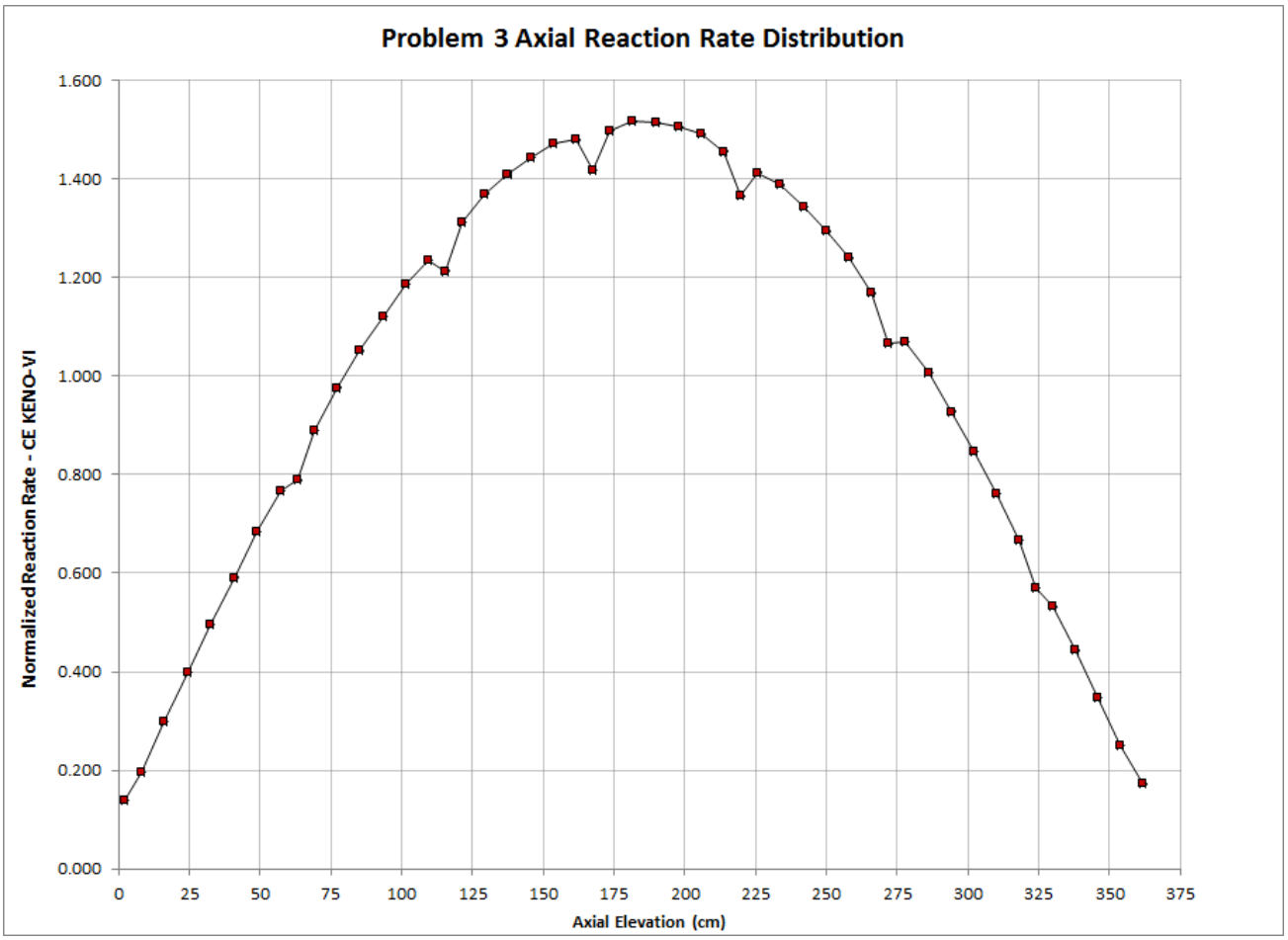


Figure P3-3: Problem 3 Axial Power

	9	10	11	12	13	14	15	16	17
9									
10	1.03642	1.00985							
11	1.03650	1.01021	1.01074						
12		1.03661	1.03822						
13	1.03491	1.00900	1.01165	1.04420	1.03181				
14	1.03160	1.00601	1.00916	1.04437	1.04983				
15		1.02530	1.02704		1.03485	1.01684	0.97396		
16	1.01136	0.98820	0.98823	1.01101	0.98354	0.96545	0.94894	0.93982	
17	0.97713	0.97292	0.97248	0.97449	0.96541	0.95579	0.94683	0.94242	0.94794

Reference Problem 3 Radial Reaction Rate Uncertainty

(CE KENO-VI 1 sigma)

	9	10	11	12	13	14	15	16	17
9									
10	0.00121	0.00120							
11	0.00121	0.00085	0.00120						
12		0.00086	0.00086						
13	0.00121	0.00085	0.00085	0.00086	0.00121				
14	0.00121	0.00085	0.00085	0.00086	0.00086				
15		0.00086	0.00085		0.00086	0.00085	0.00117		
16	0.00118	0.00084	0.00083	0.00085	0.00084	0.00082	0.00081	0.00114	
17	0.00116	0.00083	0.00083	0.00083	0.00082	0.00081	0.00080	0.00080	0.00115

Figure P3-4: Problem 3 Radial Power Distribution

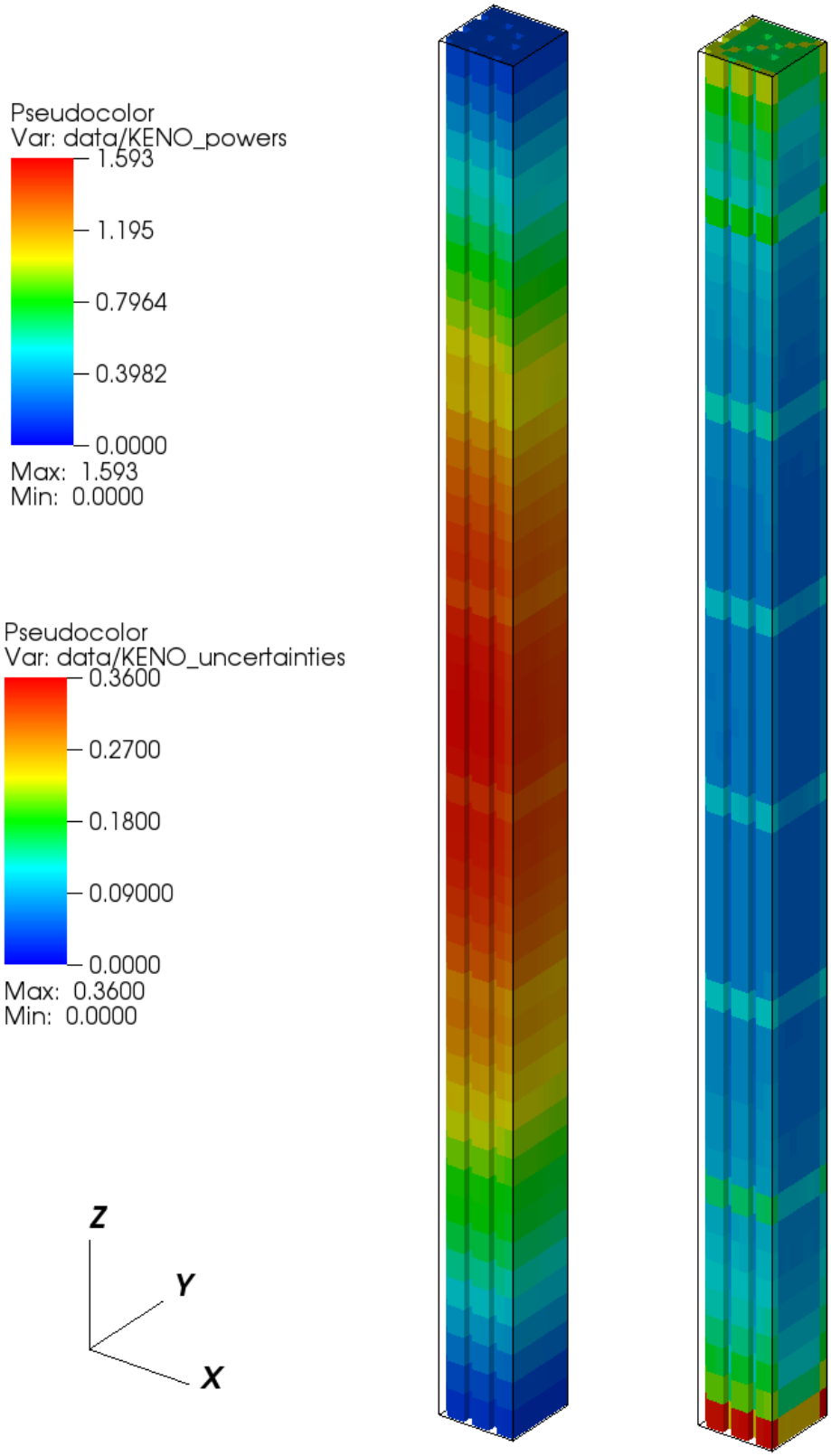


Figure P3-5: Problem 3 Visualization of Pin Power Results and Uncertainties

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 rod reactivity worth, a critical reactor physics parameter which is used for benchmarking 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). 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 B4C (1.6) aborbers 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, simple from the center of the WBN1 core described in 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.

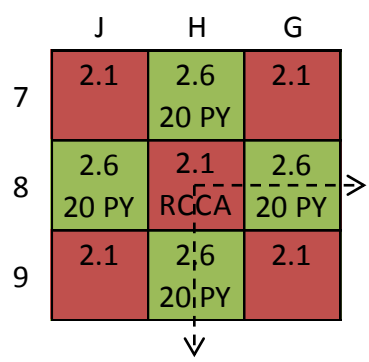


Figure P4-1: Problem 4 Assembly, Poison, and Control Layout

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	600 K	--
Inlet Coolant Density	0.743 g/cc	2.0
Reactor Pressure	2250 psia	3.
Boron Concentration	1300 ppm	3.
RCCA Position	167 steps withdrawn	--

- 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 position of the RCCA is selected as approximately the critical position for the specified boron concentration. The location of the tip of the rod is considered to be at:

$$17.031 + 167 \times 1.5875 = 282.14\ cm$$

- 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.

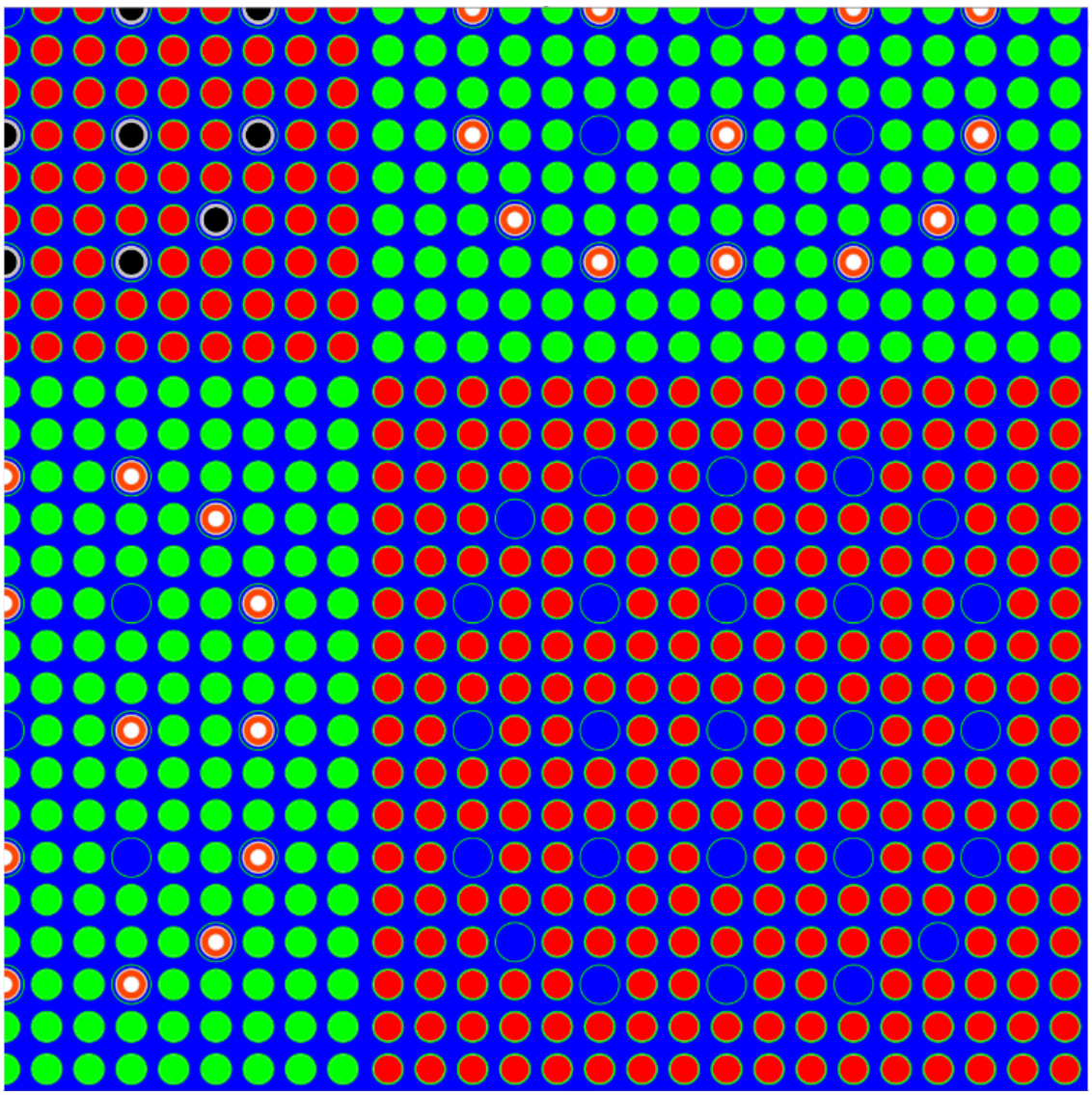


Figure P4-2: Problem 4 Radial Geometry

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

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
- 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

Problem 4 does not have a reference solution yet. As the problems get larger, they become increasing more difficult to model with CE Monte Carlo techniques and even more difficult to get acceptable reaction rate uncertainties. These efforts are ongoing within AMA.

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