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Initial Boiling Water Reactor (BWR) Input Specifications

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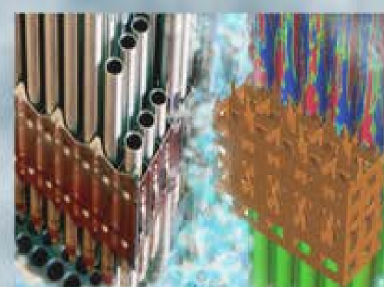
Core Physics



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REVISION LOG

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0	02/28/2015	All	Original Report for L3:PHI.VCS.P10.02

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ACRONYMS

BWR	Boiling Water Reactor
CASL	Consortium for Advanced Simulation of Light Water Reactors
OEM	Original Equipment Manufacturer
PWR	Pressurized Water Reactor
VERA	Virtual Environment for Reactor Analysis

1. INTRODUCTION

Part of the scope for CASL Phase 2 is the capability to model Boiling Water Reactor (BWR) multi-bundle configurations with the VERA Core Simulator (VERA-CS). The first step in adding BWR capability to VERA-CS is to model 2D assemblies with MPACT neutronics. Once this is finished, additional steps will be defined to model 3D BWR assemblies and to couple the neutronic models with CTF thermal-hydraulics and BISON fuel performance.

This report is part of the CASL Milestone L3:PHI.VCS.P10.02 to define the initial BWR input specifications for a BWR assembly. This Milestone has been defined to support the DOE reportable Milestone L2:RTM.P10.01, due later this year, to “Demonstrate a BWR subregion neutronics capability using a planar pin-resolved MOC methodology”.

It should be noted that this report defines *initial* BWR capability. As Phase 2 progresses, additional BWR capability will be defined to cover 3D coupled calculations.

2. BWR ASSEMBLY FEATURES

There are currently 100 operating commercial power reactors in the US. 65 of these are Pressurized Water Reactors (PWRs) and 35 are BWRs.

All of the BWR reactors in the US were designed and built by General Electric. However, there are now three different fuel vendors that supply BWR fuel:

1. Global Nuclear Fuel (GNF) (designs based on previous General Electric (GE) designs)
2. Areva (designs based on previous Siemens designs), and
3. Westinghouse (designs based on previous ABB designs).

Each fuel vendor has a slightly different assembly design. For our additional capability, we will focus on older GE designs that have dimensions that are in the public domain. In particular, we will consider specified in the Peach Bottom Turbine Trip Benchmark [2]. We will add additional features to model newer designs as applications arise.

2.1 Geometry Features

A typical GE BWR lattice is shown in Figure 1. One of the major differences between a BWR assembly and a PWR assembly is that the BWR assembly is surrounded by a channel box to isolate the coolant flow and void distribution within an assembly. Another major difference is that BWRs have large “control blades” that are inserted in the gaps between assemblies, while PWRs have “control rods” that are inserted in the guide tubes of assemblies. Finally, the third difference is that the BWR coolant is at a lower pressure and voids at normal operating conditions.

There are many minor features that differentiate different BWR designs from different vendors. These include thick channel box corners, “thick-thin” channel boxes, different control blade designs, and different water rod geometries. We will not attempt to model every unique BWR design, but will instead focus on the geometry features of the most common BWR assembly designs found used in the US, and on designs that have non-proprietary dimensions available.

Unlike PWRs, BWRs can change the number of fuel rods and guide tube designs inside the assemblies. The first commercial reactors started with 7x7 fuel designs, but reactors have transitioned to more economical designs that use 8x8, 9x9, and 10x10 fuel. All BWRs in the US are currently using 10x10 fuel designs, but some international reactors still use 9x9 fuel.

Most modern BWR 10x10 designs have proprietary dimensions that are not in the public domain. The dimensions for the older 8x8 GE designs are part of the public domain. In particular, there is a complete specification for the Peach Bottom reactor that is used as a benchmark problem to model turbine trip transients [2]. Since these designs are in the public domain and used for validation, we will focus our initial development activities on these designs. We will also include oversized water rods that take 2x2 pincells because these are common to many BWR and PWR designs. Additional capabilities will be added to model newer designs as applications arise.

The initial list of BWR features that will be supported in VERA-CS is:

- channel box with rounded corners
- wide and narrow gaps on the outside of the channel box
- ability to specify different void/density inside and outside the channel box
- GE Original Equipment Manufacturer (OEM) control blade design
- large water rods that take 2x2 pincells

If time permits, the second priority items to be supported are:

- thick channel box corners
- "square" water rods with rounded corners (Areva Atrium designs)
- 2 large water rods that together replace 7 pincells (GE11 designs)
- large water rods that are slightly larger than 2x2 pincells (GE9 design)

Finally, BWR features that will NOT be supported at this time include:

- Westinghouse SVEA water cross designs
- thick-thin channel box designs
- non-OEM control blade designs
- diagonal symmetry
- BWR detectors (not needed for mini-configurations)
- Mixed configurations assemblies that have different number of rods (e.g. 8x8 assemblies and 10x10 assemblies in the same problem)

2.2 Rotations

BWR assemblies have two different sized "gaps" on the outside of the channel box. There is a "wide gap" on two adjacent sides, and a "narrow gap" on the other adjacent sides. These gaps are shown as dimensions "A" and "D" in Figure 1. Control blades are placed in the wide-wide corners, and detectors can be placed in the narrow-narrow corner. Sometimes the wide and narrow gaps have the same physical size, but they are still referred to as the wide and narrow gap to indicate where the control blade and detectors are placed.

When placed in a core, each assembly is rotated so that the wide-wide corners meet in a control blade location, and the narrow-narrow corners meet in a detector location. These rotations are fixed, and cannot be changed. (This is different from a PWR, where some PWR vendor designs allow the utilities to rotate assemblies arbitrarily.)

Since the rotation map is fixed, the user is not allowed to specify a "rotate_map" in the input. A check should be made to make sure that the rotation map is not present in BWR cases. The code should manually specify the rotation map like the following example:

```
rotate_map
  2 3 2 3 2 3
  1 0 1 0 1 0
  2 3 2 3 2 3
  1 0 1 0 1 0
  2 3 2 3 2 3
  1 0 1 0 1 0
```

A rotation of "0" means that the wide-wide gap is in the upper left corner. A rotation of "1" means to rotate the assembly clockwise 90 degrees, a rotation of "2" means to rotate the assembly clockwise another 90 degrees, and so on.

All operating BWR's have an even number of assemblies across the major axis and a wide-wide gap (control rod) in the center of the core. The internal rotation map should be generated such that the wide-wide gap is in the center of the core.

For single-assembly cases, the wide-wide gap should be in the upper left corner. This is the standard orientation for single assemblies.

At this time, only single-assemblies, or configurations with an even number of assemblies across, are allowed. In the future, we may add the ability to run special cases where there are an odd number of assemblies across, or where the narrow-narrow gap is in the center of the core. This should be considered future development and is not part of the initial development.

2.3 Material Features

A diagram showing the material compositions from Reference [1] is shown in Figure 2.

BWR assemblies typically have many more enrichments zones than PWR assemblies and use gadolinium as a burnable poison. This example has fuel rods with 10 different enrichments and two gadolinium rods.

The current VERA-CS input can model multiple enrichment zones and gadolinium rods, so no additional work is needed to support BWR fuel materials.

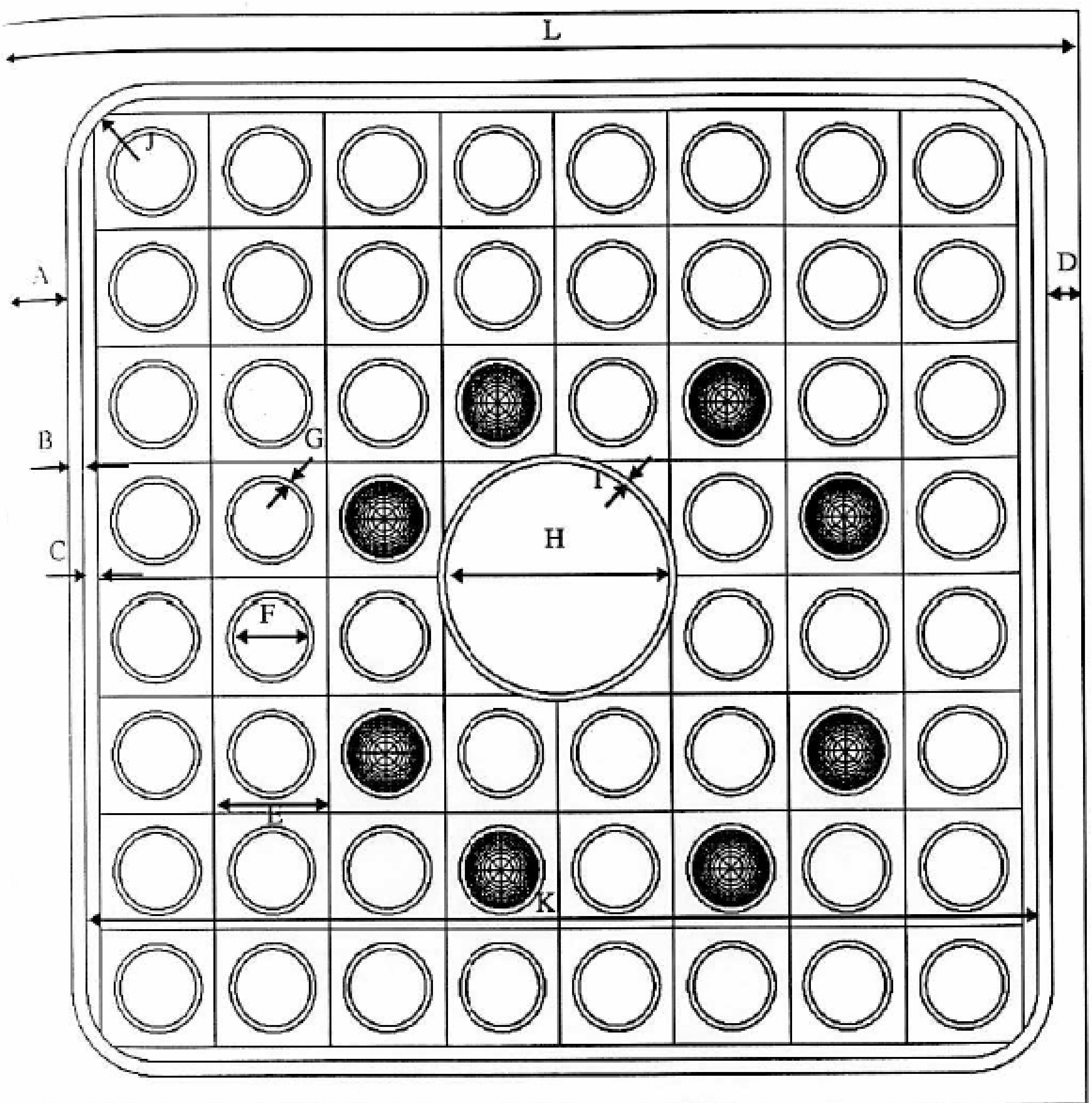


Figure Dimensions

A = 0.9525 cm	G = 0.08128 cm
B = 0.2032 cm	H = 3.2004 cm
C = 0.20066 cm	I = 0.1016 cm
D = 0.47498 cm	J = 0.9652 cm
E = 1.6256 cm	K = 13.40612 cm
F = 1.06426 cm	L = 15.24 cm

Gd Rod Radii (Cm)

Ring	Radius	Ring	Radius
1	0.16827	6	0.41219
2	0.23798	7	0.44521
3	0.29146	8	0.47595
4	0.33655	9	0.50482
5	0.37627	10	0.53213

Figure 1: Geometry description for GE9 assembly [1]. (The oversized water rod is not included in the initial specification)

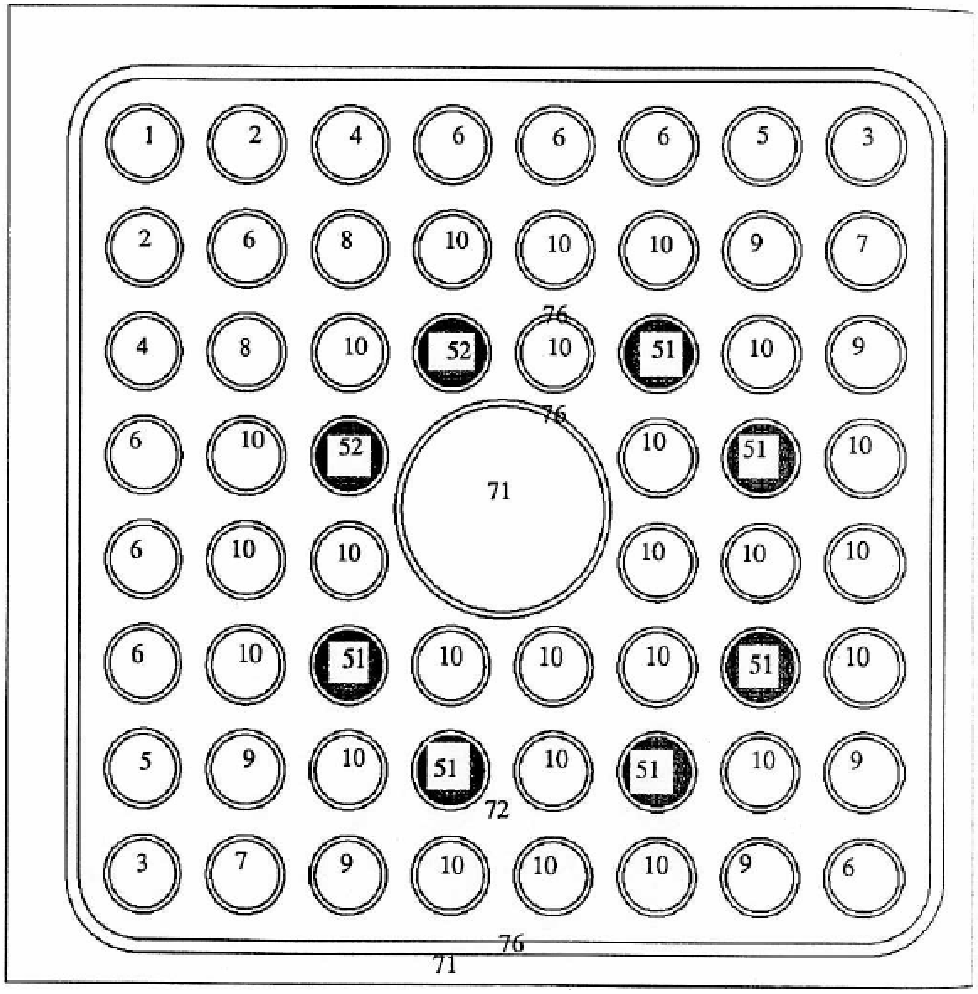


Figure 2: Material Composition for GE9 Assembly. The solid rods are gad rods [1].

3. INPUT

The following subsections describe the new input cards needed to define BWR geometry.

3.1 STATE Block

Pressure

The pressure input card already exists, but is required for BWR cases to determine the void. A standard operating pressure in a BWR is 1040 psia.

Void

The only new input card in the STATE block is a map specifying the void inside the channel box for standalone cases with no feedback.

void void_map

void_map – 2D core map showing the in-channel void concentration (%)

The void outside the channel box is assumed to be zero.

For cases with no feedback, the coolant density will be calculated at the saturation conditions corresponding to the core pressure, and the void specified in the "void" input.

For cases with feedback, the "void" card will be ignored and the coolant void will be calculated in the thermal-hydraulic models (analogous to "tfuel" and "modden").

The cards "modden" and "void" cannot be used in the same input deck. The code should check for this condition and print an error message if it is encountered.

Symmetry

BWR assemblies usually have different wide and narrow gap widths, so specifying quarter-assembly symmetry is usually not an option. Instead, BWR assemblies tend to be run with diagonal symmetry with a line of symmetry running from the wide-wide corner to the narrow-narrow corner.

Diagonal symmetry is very useful when running single-assembly cases to decrease run-times. However, due to the complexity of adding diagonal symmetry to the neutronics and T/H models, we have decided to defer diagonal symmetry until a later date. In VERA-CS, all BWR cases must be run with "full" assembly symmetry. Core calculations can still be run in quarter-symmetry, but each assembly must be "full".

3.2 CORE Block

Reactor Type

A reactor type card has been added to specify if this is a BWR core. This flag is necessary to indicate control rod positions and whether the wide and narrow gaps are specified.

reactor_type type
    type – "BWR" or "PWR" (default "PWR")

Control Blade Location Convention

In BWRs, the control blades and detectors are inserted "between" assemblies, and not "in" the assemblies like a PWR. Since all of the input maps are assembly-based, we will use the convention that a control blade or detector is present in the gap above and to the left of the assembly indicated in the map.

For example, the following map shows a 4x4 assembly core with a control blade located in the middle of the core. The control blade location is located above and to the left of the assembly location marked with a "1".

```
crd_map
    - - - -
    - - - -
    - - 1 -
    - - - -
```

In addition, note that all operating PWRs have an odd number of assemblies across the core, so the center of the core occurs in the middle of an assembly. All operating BWRs have an even number of assemblies across the core, so the center of the core is a control blade location. This makes quarter-core BWR cases easier to model because they don't have half-assembly or half-pin boundaries.

Note that it is not valid to fill the "crd_map" completely with control rod locations. This is because control rods can only be placed in locations with a wide-wide gap. The code should add sufficient error checking to make sure that a user does not add a control rod to a location that is not a wide-wide gap. Likewise, error checking should be added to make sure detectors are only placed in locations with a narrow-narrow gap.

3.3 ASSEMBLY Block

Outside Gaps

The assembly gap widths on the outside of the channel box are defined with:

gap gapw gapn
    gapw – assembly gap in wide channel (north and west) (cm) (dimension "A" in Figure 1)
    gapn – assembly gap in narrow channel (south and east) (cm) (dimension "D" in Figure 1)

Control blades are inserted in wide gaps and detectors are inserted into narrow gaps.

Note that this card is not valid for PWR's. The "gap" card specifies the gap on the outside of the channel box. The assembly gap for PWR's is equivalent to the "internal gap" described below.

Channel Box

The channel box geometry is defined with:

channel_box chanmat chanth chanrad cornerth cornerlen
- chanmat – channel material (string)
- chanth – channel box thickness (cm) (dimension "B" in Figure 1)
- chanrad – channel box inside corner radius (cm) (dimension "J" in Figure 1)
- cornerth – thickness of channel box corner (if thick corner design is used) (cm)
  (Optional – defaults to chanth if not input, or input as a zero)
- cornerlen – length of thick corners measured from the channel corner (cm)
  (Optional – enter as zero if not using thick channel corners)

The channel box thickness is shown as dimension "B" in Figure 1. The channel box radius is shown as dimension "J".

Channel box thicknesses are typically referred to as "80 mil" (0.08 inches), "100 mil" (0.1 inches), and "120 mil" (0.12 inches). These must be converted to cm for the input.

Internal Gaps

The channel internal gaps are shown as dimension "C" in Figure 1. The internal gap is not input, but is calculated in the following manner. The total assembly pitch is given on the "apitch" card. The wide and narrow gaps are specified by "gapw" and gapn". The channel thickness is specified by "chanth". The gap on the inside of the channel box is then calculated as:

Inside gap = (apitch – 2*chanth – gapn – gapw)/2

A check should be included in the code to make sure the inside gap is equal to or greater than zero.

Large Water Rods

A large circular water rod is defined by defining an oversized "cell" card and then placing 4 cell cards together in a map as shown below. A "cell_large4" card is used to specify that this is a large water rod that takes 2x2 pincell locations.

cell_large4 cellname
- cellname – name of cell that describes 2x2 circular water rod.
  This card will set the cell type to "large4" in the parameter list.

```
! the following is a large water rod card.
! The pin pitch is 1.6256 cm and the water rod radius is 1.6 cm
  cell WR 1.58 1.6 / mod zirc4
  cell_large4 WR    ! specify that this is a large water rod
  lattice LAT
    1
    2  6
    4  8 10
    6 10 52 WR
    6 10 10 WR WR
    6 10 51 10 10 10
    5  9 10 51 10 51 10
    3  7  9 10 10 10  9  6
```

The “cell_large4” card will set the cell type to “large4” in the CELL parameter list.

The code should check to make sure that the radius of the large water rod is less than the pin pitch. (This check may be relaxed in the future if GE9 designs are supported.)

In addition, if a cell is specified as “large4”, then the code should check that there are 4 cell names in the lattice map arranged in a 2x2 configuration.

An input card will be added in the future to describe square Atrium water rods. In the case of square rods, the dimensions on the cell card will be interpreted as sides of a square instead of radii.

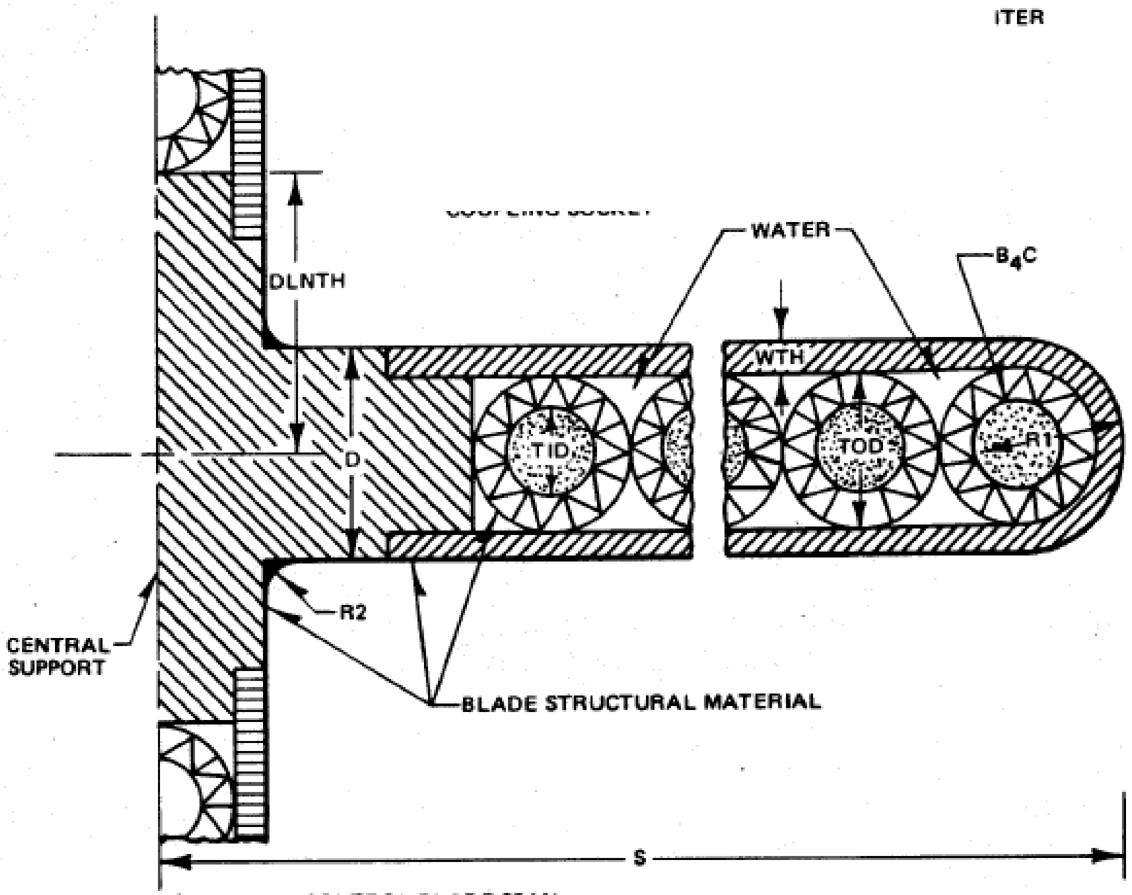
The “large4” input card will also be used to model large water rods in PWR reactors (i.e. some CE PWR designs).

Symmetry in Assembly maps

The user is allowed to input assembly maps using diagonal symmetry. The input processor will expand the assembly maps to full-geometry before writing to the XML file (just like quarter-symmetry assembly maps are currently mapped).

3.4 CONTROL Block

A schematic of a GE OEM control blade is shown in Figure 3. The dimensions for this blade are given in Table 1.



S	CONTROL BLADE SPAN
D	CONTROL BLADE FULL THICKNESS
DLNTH	DEAD LENGTH, i.e., CENTRAL STRUCTURE LENGTH
TID	TUBE i.d.
TOD	TUBE o.d.
WTH	SHEATH THICKNESS
NBKT	NUMBER OF BLANK TUBES ADJACENT TO CENTRAL STRUCTURE PER WING
R1	BLADE TIP RADIUS
R2	BLADE FILLET RADIUS

Figure 3: Control Blade Geometry [3]

Table 1: Control Blade Data [2]

Shape	Cruciform	
Control Material	B_4C granules in Type-304 stainless steel tubes and sheath	
Material Density	70% of theoretical density (TD)	
Number of Tubes per Rod	84 (21 per wing)	
Tube Outside Diameter (OD)	0.188 in	0.47752 cm
Tube wall thickness	0.025 in	0.0635 cm
Control Blade Span	4.875 in	12.3825 cm
Control Blade Full Thickness	0.3120 in	0.79248 cm
Control Blade Tip Radius	0.156 in	0.39624 cm
Sheath Thickness	0.056 in	0.14224 cm
Central Structure Wing Length	0.7815 in	1.98501 cm

*Some partial dimensions do not add to overall dimensions due to designed clearances between tube and sheath
** These dimensions are consistent with Reference [3], except more significant digits are kept in the unit conversion.

The control blade absorber tube should be defined with a "cell" card. The other dimensions are defined with the "blade" card:

blade ntube tubecell bladespan bladeth bladerad bladesheath bladewing blademat

ntube – Number of absorber tubes in one wing of a control blade
tubecell – cell label for absorber tube
bladespan – Control blade span (cm) (dimension "S" in Figure 3)
bladeth – Control blade full thickness (cm) (dimension "D" in Figure 3)
bladerad – Control blade tip radius (cm) (dimension "R1" in Figure 3)
bladesheath – Control blade sheath thickness (cm) (dimension "WTH" in Figure 3)
bladewing – Central Structure Wing Length (cm) (dimension "DLNTH" in Figure 3)
blademat – Sheath and wing material (string)

Note that the absorber tube outer diameter (ATOD) is smaller than "bladeth" – 2*"bladesheath". A check should be included in the code for this.

Another check should be added to make sure ntube*ATOD is less than "bladespan" – "bladewing" – "bladesheath". The absorber tubes should be distributed evenly within the blade.

Additional input will have to be defined to model 3D control rods. This is outside of the scope of the initial input specifications.

3.5 DETECTOR Block

BWR detectors are not supported at this time. Detectors are not needed for "mini-core" configurations, but will be needed for full-core models.

4. BWR PROGRESSION PROBLEMS

It is useful to add BWR features in a progressive manner and test at each stage. The following progression is recommended:

1. Pin cell calculations at BWR conditions. There is no new code features needed for this step, but we can test cross sections using BWR fuel rod dimensions and void.
2. Peach Bottom Assemblies [2] with no control blades. The Peach Bottom assemblies have a standard channel box and gaps, but do not have large water rods.
3. Peach Bottom Assemblies with control blades.
4. Assemblies with large 2x2 water rods (generic dimensions, including both BWR and PWRs)
5. Atrium square channel box (if time permits)
6. 3D Assemblies with no feedback or control blade (stretch goal, only if time permits)

After each of these progression problems have been completed, they should be checked in the repository and tested against Monte Carlo calculations. It is much easier to test and debug as we develop, rather than wait until the very end.

REFERENCES

[1] D. J. Kelly, "Depletion of a BWR Lattice Using the RACER Continuous Energy Monte Carlo Code," *Proc. Int. Conf. on Math and Comp., Reactor Physics, and Env. Analysis*, Portland, Oregon, USA, April 30-May 4 (1995).

[2] J. Solis, K. N. Ivanov, B. Sarikaya, A. M. Olson, K. W. Hunt "Boiling Water Reactor Turbine Trip (TT) Benchmark, Volume I: Final Specifications," NEA/NSC/DOC(2001)1 (Feb 2001). https://www.oecd-nea.org/science/docs/2001/nsc-doc2001-1.pdf

[3] I. C. Gauld, "SCALE-4 Analysis of LaSalle Unit 1 BWR Commercial Reactor Critical Configurations," ORNL/TM-1999/247 (Mar 2000).

APPENDIX A: PARAMETER LIST SUMMARY

This section summarizes the input parameters that are written to the XML file.

STATE

Entry name	Description	Type	Valid values	Default	Units	Required
void_map	core map of void fraction	double	>= 0.0	0%	%	No

CORE

Entry name	Description	Type	Valid values	Default	Units	Required
reactor_type	Reactor type	string	"PWR", "BWR"	"PWR"	–	No

ASSEMBLY

Entry name	Description	Type	Valid values	Default	Units	Required
gapn	Assembly gap in wide channel	double	>= 0.0		cm	Yes
gapw	Assembly gap in narrow channel	double	>= 0.0		cm	Yes
chanmat	channel box material	string			–	Yes, if channel boxes are used
chanth	channel box thickness	double	> 0.0		cm	
chanrad	channel box inside corner radius	double	>=0.0	0	cm	
cornerth	thickness of channel box corner if thick corner design is used	double	>= 0.0	chanth	cm	
cornerlen	length of thick corners measured from the channel corner	double	>= 0.0	0	cm	

ASSEMBLY/CELL

Entry name	Description	Type	Valid values	Default	Units	Required
type	The type of cell being described	string	"fuel", "large4", "other"		–	Yes

CONTROL

Entry name	Description	Type	Valid values	Default	Units	Required
ntube	Number of absorber tubes in one wing of a control blade	int	> 0		–	Yes, if blade present
tubecell	Cell label that describes absorber tubes	string			–	
bladespan	Control blade span	double	> 0.0		cm	
bladeth	Control blade full thickness	double	> 0.0		cm	
bladerad	Control blade tip radius	double	> 0.0		cm	
bladesheath	Control blade sheath thickness	double	> 0.0		cm	
bladewing	Central Structure Wing Length	double	> 0.0		cm	
blademat	Sheath and wing material	string			–	

APPENDIX B – SAMPLE BWR INPUT

The following input deck is one of the six Peach Bottom 2 designs from Reference [2]. The BWR specific input cards are highlighted in red.

Input decks from all six PB2 designs have been loaded to the git repository, along with a modified GE9 input deck (modified so that the large water rod fits in 2x2 pincells).

```
[CASEID]
  title 'BWR Peach Bottom 2 Design 6 8x8'

!------------------------------------------------------------------------------
!
!  Design 6 (LTA)
!  8x8 with 100 mil channel
!  2 water rods
!  2% gad
!
! Reference:
!   NEA/NSC/DOC(2001)1
!   BOILING WATER REACTOR TURBINE TRIP (TT) BENCHMARK
!   Volume I: Final Specifications
!   February 2001
!
!------------------------------------------------------------------------------

[STATE]
  power    100.0
  tinlet   575 F   ! *** average operating temperature, not inlet
  tfuel    900 K
  pressure 1040    ! psia
  sym      full

  void
    40.0

!** at void 00,  rho=  0.736690 g/cc
!** at void 40,  rho=  0.457023 g/cc
!** at void 70,  rho=  0.247273 g/cc


[CORE]
  reactor_type BWR
  size   1
  apitch 15.24
  height 1.0
  rated  0.01 0.01   ! *** approximate

  core_shape
    1

  assm_map
    ASSY

  bc_rad reflecting
  bc_top reflecting
  bc_bot reflecting
```

```
  mat zirc2  6.5514 zirc4      ! zirc density p. 39
  mat zirc4  6.5514 zirc4
  mat he    0.000176 he

[ASSEMBLY]
  npin   8
  ppitch 1.6256          ! pin pitch - does not include channel gaps

!*** 100 mil design
  gap    0.9017 .42418   ! wide and narrow channel gap (cm)
  channel_box zirc4 0.254 0.9652 0.0 0.0   ! channel dimensions

!*** enrichments p. 18
!*** density and materials p. 12

  fuel U301  10.32 94.5 / 3.01
  fuel U222  10.32 94.5 / 2.22
  fuel U187  10.32 94.5 / 1.87
  fuel U145  10.32 94.5 / 1.45
  fuel U3G   10.23 94.5 / 3.01 / gad=2.0

  cell 1   0.5207 0.53213 0.61341 / U301 he zirc2
  cell 2   0.5207 0.53213 0.61341 / U222 he zirc2
  cell 3   0.5207 0.53213 0.61341 / U187 he zirc2
  cell 4   0.5207 0.53213 0.61341 / U145 he zirc2
  cell 5G  0.5207 0.53213 0.61341 / U3G  he zirc2
  cell WR         0.67437 0.75057 /    mod  zirc2  ! large WR

  lattice LAT
    4
    3  2
    2  1  1
    2  5G 1  1
    2  1  1 WR  1
    2  1  1  1  1  1
    2  1  5G 1  1  1 5G
    3  2  1  1  1  1  1  2

  axial ASSY 0.0 LAT 1.0

[MPACT]
  num_space      1
  num_angle      8
  num_threads    1

[INSILICO]
  num_blocks_i   4
  num_blocks_j   4
```