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BWR and PWR Lattice Design with Polaris



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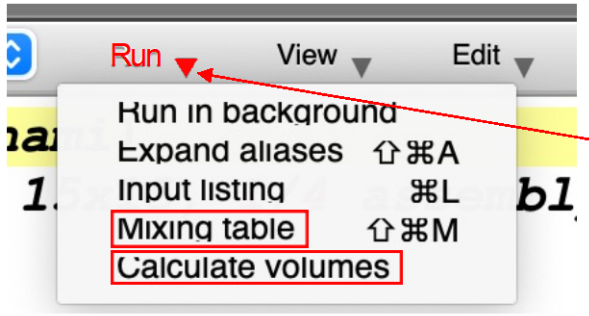
SCALE 6.3.1 last revision (May 2024)

Learning Goals

- Model different PWR and BWR geometries using available pin, box, control rod, and cross cards.
- Define material compositions for fuel and structural materials using predefined materials, as well as weight or number density fractions.
- Explore different methods for setting material states, including temperature, density, and void conditions.
- Perform depletion calculations utilizing several convenience cards.
- Generate few-group cross sections for core simulators.
- Utilize advanced options to enhance solution fidelity beyond the default settings.

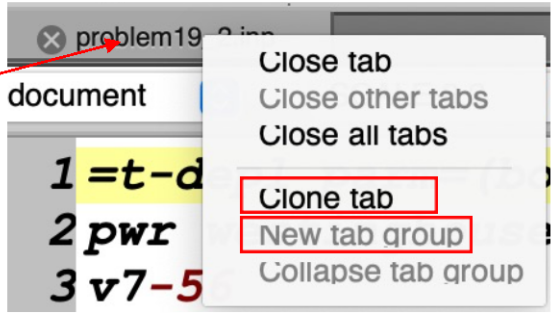
Fulcrum cheat sheet

- Shortcuts:
  - **CTRL+SPACE** – auto-completion
  - **CMD+/** (Mac) **CTRL+/** (Windows/Linux) – comment in/out input lines
  - **CTRL+E** (Windows/Linux) **CMD+E** (Mac) – evaluate selected mathematical expression
  - **ALT+MOUSE SELECTION** – column-wise text selection and modification
  - **SHIFT+ENTER** – jump to next row, start at indentation of current row
- Input check:
  - **Validation** window through lower right corner
  - **View** geometry
- Additional features:
  - **Run > Mixing table** – Check compositions through mixing table
  - **Run > Calculate volumes** – Calculate volumes
  - **Right click on tab > New tab group** – Use side-by-side view through multiple tabs
  - **Right click in Mesh panel within geometry visualization** – Allows loading of new mesh data for data overlay
  - **Right click in the Messages panel** – Allows termination of running jobs
  - **Right click on "View origin" within geometry visualization** – Explicit specification of view origin coordinates



Click on arrow next to Run to see options

Right click on Tab (file name) to set up multiple tabs



- Notes:
  - Auto-completion does not work if there is a validation error (including incomplete input) *above* the current location
  - Validation of *array* input is limited and cannot check (1) the consistency between number of specified elements vs. provided unit number and (2) whether or not the array completely fills a shape → use visualization and run problem with *parm=(check)*
  - Validation of *hole* placement is limited and cannot check overlap between holes or holes with other shapes → use visualization and run problem with *parm=(check)*

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Polaris Input Basics



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Polaris Modeling Philosophy

"Common sense is not so common" - Voltaire

Sequence of input blocks is not important

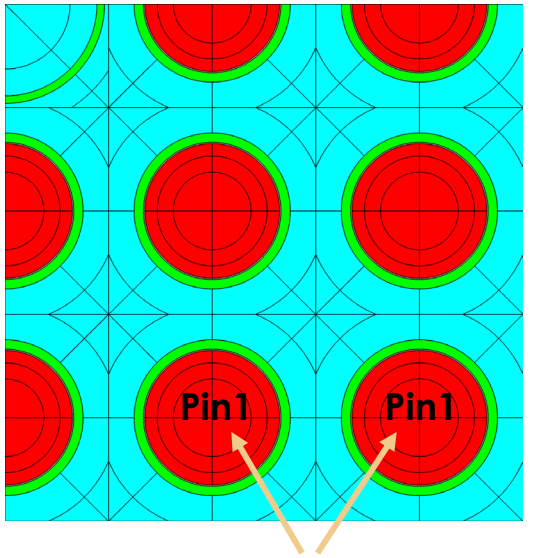
- *You can define your pin layout before you specify what is inside each pin*

Compositions make up materials

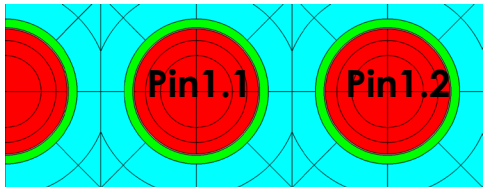
- *3% enriched UO_2, water, Zircaloy-2 are compositions for fuel ,clad, moderator materials (mixtures in SCALE terminology)*

Two materials can have the same composition, and they are still considered as two different materials (numbered internally)

- *two identical fuel pins with the same initial composition of 3% UO_2 can have different nuclide inventory when depleted.*



3%enriched UO_2



Polaris Modeling Philosophy

"Code should have as many defaults as possible to make model input easy and simple"
- Matt & Will

User has the option to name each material separately or use a common name and differentiate it by a material number

- *myfuel, your fuel vs FUEL.1 FUEL.2*
- *use of common names has its advantages: state properties, histories can be assigned as a group (e.g., FUEL: temp=1000 instead of myfuel: temp=1000, your_fuel: temp=1000)*
- *specific names have default treatments(e.g., FUEL is known as fuel which has 8 segments, colored red, shielded and depleted)*

Compositions can have default reference densities based on the system card.

User has option to skip order on an input card, if explicit keywords are used

- *mycomp: 10.26 600 vs mycomp: temp=600 dens=10.26*

General Modeling Philosophy

"Risk comes from not knowing what you're doing"
- Warren Buffet

Defaults are great, take advantage of them; however, they can hide your mistakes

- Check output and make sure what code sees is what you want to model
- SCALE suit codes are extensively verbose in their output as a coding practice

Follow a natural order in your model from simple to complex

1. Title of your work
2. Comments/references (lots of)
3. Nuclear data
4. Materials/compositions
5. Geometry from smallest unit to the largest (fuel pin , pin map)
6. Power, state history (burnup, boron history, fuel temperature changes etc.)

Ugur's Philosophy

- *"A wise man can learn more from a foolish question than a fool can learn from a wise answer." — Bruce Lee*

```
=polaris_6.3
%-------------------------------------%
% general options
%-------------------------------------%
title "W17x17 pin cell"
      "Polaris training"

%-------------------------------------%
% 252-group ENDF/B-VII.1 library
%-------------------------------------%
lib "v7-252"

   % or

lib "fine_n"

%-------------------------------------%
% 56-group ENDF/B-VII.1 library
%-------------------------------------%
lib "v7-56"

   % or

lib "broad_n"




end
```

Basics

- **title** - optional
  - double quotes
  - one or more titles allowed
- comment **%**
  - does not have to be at the first column
  - cannot appear INSIDE cards
- **lib** (or **library**) - optional
  - “v7-252” or “fine_n”
  - “v7-56” or “broad_n”
  - default “v7-252”

geom

```
=polaris
%--------------------------------------%
% general options
%--------------------------------------%
title "W17x17 pin cell"
lib "broad_n"
%--------------------------------------%
% geometry
%--------------------------------------%
geometry W17 : ASSM npins=1
                    ppitch=1.26
                    sym=FULL

   %equivalent to

geom W17 : ASSM 1 1.26 FULL

   %equivalent to

geom W17 : ASSM 1 sym=FULL
                      ppitch=1.26

   %equivalent to

geom W17 : ASSM 1 1.26


end
```

geom GNAME : ASSM|REFL npins=Int ppitch=Real [sym=FULL|SE]

- geom or geometry – geometry card
- GNAME – user geometry name
- ASSM – indicates assembly geometry
- npins - # of pins on side of the assembly
- ppitch – pin pitch (cm)
- sym – optional symmetry specification
  - FULL or SE
  - default FULL
- Keywords npins=, ppitch=, and sym=
  - Optional if in correct order
  - Required once out of order

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Material Definition



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Compositions and Materials

- Basic Concept
  - composition defines a set of nuclides and their relative distribution in the compostion
  - material (aka mixture) is a composition at a given density and temperature
  - same composition can be used to define multiple materials
  - A composition can be FORMed from multiple compositions
- Naming convention
  - composition: what is it made of? (zirc4)
  - material: which unique region is it used in? (CLAD.1)

- Several comp cards exists

comp CNAME : NUM …
define by atom %
comp CNAME : WT …
define by weight %
comp CNAME : FORM …
define chemical compound
comp CNAME : CONC …
define number densities
comp CNAME : LW …
define borated water
comp CNAME : UOX …
define UO2 with U^{235} enrichment weight %
comp CNAME : ENRU …
define U with U^{235} enrichment weight %
comp CNAME : UN …
define UN with U^{235} and N^{15} enrichment weight %

Compositions

```
=polaris_6.3
%-------------------------------------%
% comp examples
%-------------------------------------%

comp D2O       : FORM 1002=2 O16=1

comp c_f30     : UOX 3.0
comp c_gdfuel  : WT GD2O3=7 c_f30=-100

comp c_waba    : CONC
           5010=2.98553E-03
           5011=1.21192E-02
           6000=3.77001E-03
           8016=5.85563E-02
          13027=3.90223E-02

comp WATER     : LW borppm=1300

        %equivalent to

comp WATER     : LW 1300

end
```

Pre-defined compositions have a reference density. User can overwrite the reference density with refdens card

Pre-defined compositions

Standard molecular compositions

CNAME	*Description*
H2O	light water with structure=BOND(H2O)
B4C	Boron carbide burnable poison material
Er2O3	Erbium oxide burnable poison material
Gd2O3	Gadolinium oxide burnable poison material
SiC	Silicon carbide
ZrH	zirconium hydride alloy with structure=CRYS(orthorhombic_zrh)
Zr5H8	zirconium hydride alloy with structure=CRYS(cubic_zrh)
ZrH2	zirconium hydride alloy with structure=CRYS(tetragonal_zrh)
fillgas	Helium gas
Cr2O3	Chromium dioxide (chromia, Cr_2O_3)
Al2O3	Aluminum dioxide (alumina, Al_2O_3)
BeO	Beryllium dioxide (beryllia, BeO)

Standard reactor mixtures and alloys

CNAME	*Description*
aic	Ag-In-Cd control rod absorber material
pyrex	Pyrex glass
zirc2	Zircaloy-2 clad material
zirc4	Zircaloy-4 clad material
ss304	Stainless Steel 304
ss316	Stainless Steel 316
inc718	Inconel 718
water	H2O with trace amount of boron
pyroc	Pyrolytic carbon, C with structure=CRYS(pyrolytic_c)
graphite	Graphite, C with structure=CRYS(hexagonal_c)

comp and mat

```
=polaris_6.3
%-------------------------------------%
% general options
%-------------------------------------%
title "W17x17 pin cell"
lib "broad_n"
%-------------------------------------%
% geometry
%-------------------------------------%
geom W17 : ASSM 1 1.26 FULL
%-------------------------------------%
% comps and mats
%-------------------------------------%
composition c_f31 : UOX 3.1
material FUEL.1 : c_f31 dens=10.26
                        temp=600

    %equivalent to

comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26 600

end
```

density definition is not required for material card if composition of the material has a reference density.

comp CNAME : UOX enr=Real

- comp or composition
- CNAME – user composition name
- UOX – indicates uranium dioxide
- enr – U-235 enrichment wt %

mat MNAME : CNAME [dens=Real] [temp=Real]

- mat or material
- MNAME – user material name (Word.Int)
- CNAME – user composition name
- dens – density (g/cm^3)
- temp – temperature (K)

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Geometry Definition



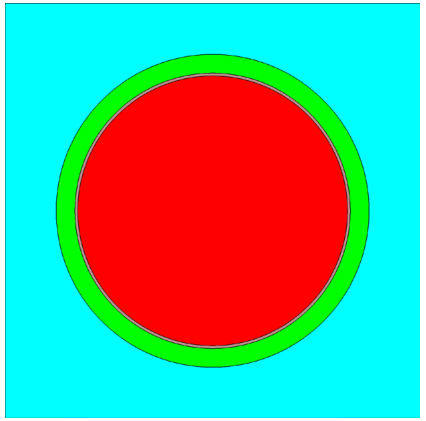
pin card

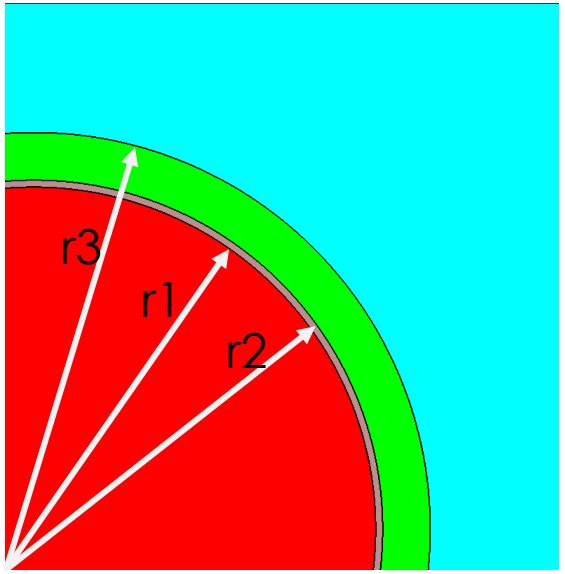
```
=polaris_6.3
%-------------------------------------%
% general options
%-------------------------------------%
title "W17x17 pin cell"
lib "broad_n"
%-------------------------------------%
% geometry
%-------------------------------------%
geom W17 : ASSM 1 1.26
%-------------------------------------%
% comps and mats
%-------------------------------------%
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26 600
mat GAP.1  : FILLGAS temp=600
mat CLAD.1 : ZIRC4   temp=600
comp WATER : LW 1300
mat COOL.1 : WATER 0.661 600
%-------------------------------------%
% pins
%-------------------------------------%
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP.1 CLAD.1 COOL.1
end
```

pin PINID : r1 r2 … ri … rN
: M1 M2 … Mi … MN [Mout]

PINID – pin identifier

- r – zone radius (cm)
- M – zone material
- Additional value of M for outermost region (Mout)





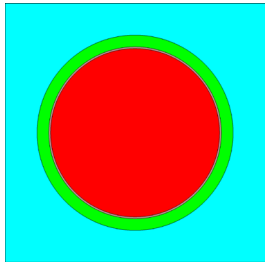
Exercise #1

- pwr-pincell.inp
  - Exercise problem #1 PWR pincell
  - Problem 1: what is the density of the coolant/moderator, what is the gap material and its density?
  - Problem 2: Convert clad material to M5 from Zirc4 and record reactivity difference
    - M5: 1% Nb, 0.125% O remaining is Zr
  - Problem 3: add 1300 ppm Boron to coolant. Hint: need to choose the right composition type

```
=polaris
%Exercise problem #1 PWR pincell
%Problem 1: what is the density of the coolant/moderator, what is the
Gap material and its density?
%Problem 2: Convert clad to M5 from Zirc4 and record reactivity
difference
%          M5: 1% Nb, 0.125% O remaining is Zr
%Problem 3: add 1300 ppm Boron to coolant Hint: need to choose the
right composition type and composition
% ---------------------------------------------
%    general options
% ---------------------------------------------
title    "Framatome assem lattice enr4.7_24Gd_enr8-CR000-DC1-PC2-TF2"
lib      "broad_lwr"
% ---------------------------------------------
%    geometry
% ---------------------------------------------
geom  mypin ASSM 1 1.26
% ---------------------------------------------
%    compositions and materials
% ---------------------------------------------
% fuel compositions
comp uox470 : UOX enr=4.70

% now adding material specs
mat FUEL.1    : uox470  dens=10.4300 temp=900
mat CLAD.1    : ZIRC4  dens=6.5083 temp=600
mat GAP.1     : FILLGAS temp=600
mat COOL.1    : H2O
% ---------------------------------------------
%    pins definitions
% ---------------------------------------------
pin A   : 0.4096   0.4180   0.4796
       : FUEL.1   GAP.1    CLAD.1  COOL.1

end
```

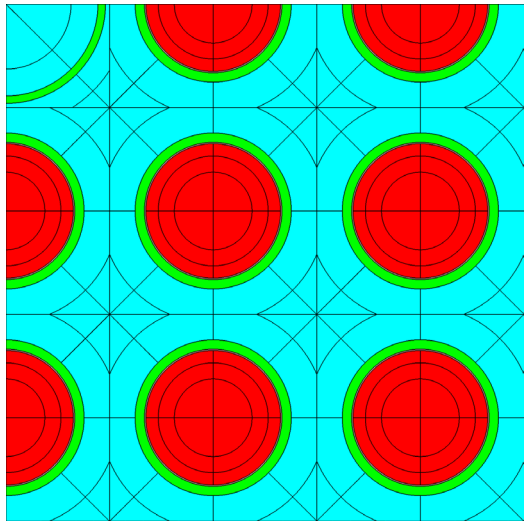


pinmap

```
=polaris_6.3
title "W17x17"
lib "broad_n"
geom W17 : ASSM 5 1.26 SE
%-------------------------------------%
% comps and mats
%-------------------------------------%
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26 600
mat GAP.1  : FILLGAS temp=600
mat CLAD.1 : ZIRC4   temp=600
comp WATER : LW 1300
mat COOL.1 : WATER 0.661 600
%-------------------------------------%
% pins and mesh
%-------------------------------------%
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP.1 CLAD.1 COOL.1
pin I : 0.559 0.605
      : COOL.1 CLAD.1 COOL.1
mesh FUEL : nr=3 ns= 4
mesh COOL : nr=2 ns= 8
%-------------------------------------%
% maps
%-------------------------------------%
pinmap
  I
  F F
  F F F
end
```

pinmap $PINID_1$ $PINID_2$ … $PINID_i$ … $PINID_N$

- supports full, quarter, or octant symmetry
- For 5x5 assembly, the pinmap can contain
  - 25 entries (geom sym=FULL)
  - 15 entries (SW diagonal sym=FULL)
  - 9 entries (SE quadrant, geom sym=SE|FULL)
  - 6 entries (SSE octant, geom sym=SE|FULL)

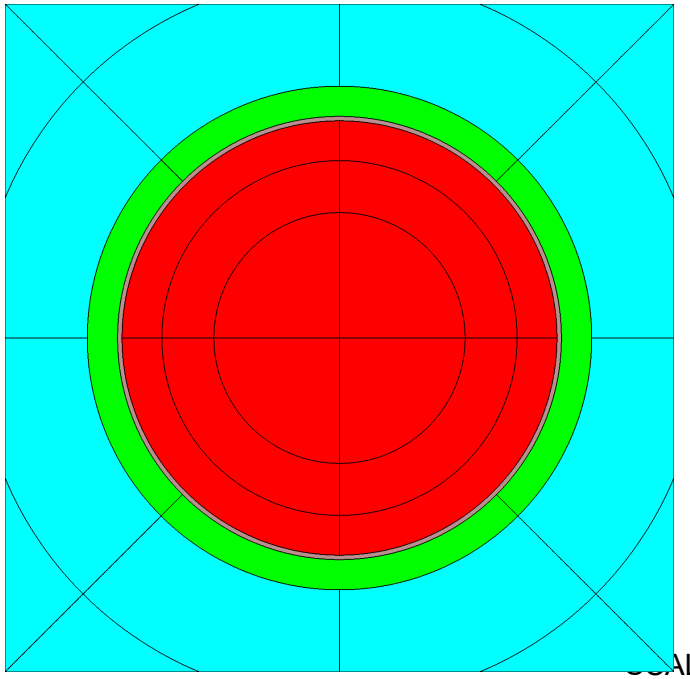


mesh part 1

```
=polaris_6.3
%-------------------------------------%
% general options
%-------------------------------------%
title "W17x17 pin cell"
lib "broad_n"
%-------------------------------------%
% geometry
%-------------------------------------%
geom W17 : ASSM 1 1.26
%-------------------------------------%
% comps and mats
%-------------------------------------%
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26 600
mat GAP.1  : FILLGAS temp=600
mat CLAD.1 : ZIRC4   temp=600
comp WATER : LW 1300
mat COOL.1 : WATER 0.661 600
%-------------------------------------%
% pins and mesh
%-------------------------------------%
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP.1 CLAD.1 COOL.1
mesh FUEL : nr=3 ns= 4
mesh CLAD :      ns=-4
mesh COOL : nr=2 ns= 8
end
```

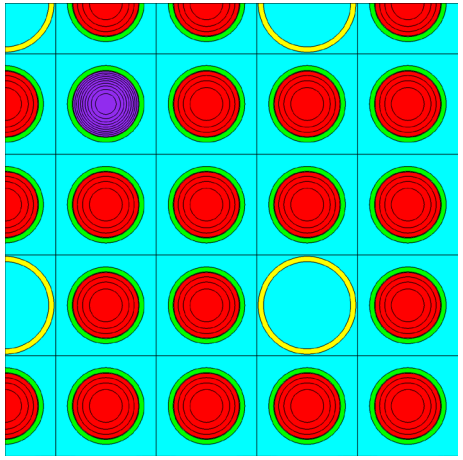
mesh MCLASS|MNAME : [nr=Int] [ns=Int]

- MNAME – the material name
- MCLASS – the 1st part of the material name
  - e.g., COOL in COOL.1
- nr – # of radial mesh for a pin, must be > 0, default 1
- ns – # of sectors for a pin, must not equal 0, negative value implies half sector offset, default 1



Exercise #2

- pwr-lattice.inp
  - Fix the input for geometry errors



```
=polaris
%Exercise problem #2 PWR lattice
%Problem 1: Fix the input file and run
%    general options
title assem lattice enr4.7_24Gd_enr8"
lib      "broad_lwr"
%    geometry
geom  mylattice ASSM 5 1.26 SE
%    compositions and materials
% ---------------------------------------------
% now adding material specs
% fuel compositions
comp uox350 : UOX enr=3.50
comp uox470 : UOX enr=4.70
comp g800 : WT GD2O3=8.00 uox350=-100
% cladding composition is a user-defined composition
comp m5      : WT
               Nb=1.0
               O=0.125
               Zr=-100
comp clgr : WT m5=4.94  m5=1.37  inc718=2.08  m5=-100
comp WATER : LW 1300
% now adding material specs
mat FUEL.1    : uox470  dens=10.4300
mat GAD.1     : g800  dens=10.0700
mat CLAD.1    : clgr  dens=6.5083
mat TUBE.1    : m5  dens=6.4800
mat GAP.1     : FILLGAS temp=600
mat COOL.1    :WATER dens=0.7
```

```
%    pins definitions
% ---------------------------------------------
pin A   : 0.4096   0.4180   0.4796
       : FUEL.1   GAP.1    CLAD.1  COOL.1
pin GD1 : 0.4096   0.4180   0.4796
       : GAD.1    GAP      CLAD.1  COOL.1

pin GT  : 0.5450   0.6120
       : COOL.1    TUBE.1
%    meshing options
% ---------------------------------------------
mesh GAP   : ns=1
mesh FUEL  : nr=4
mesh GAD   : nr=10
mesh COOL  : nx=4 ny=4
pinmap
 GT
 A   GD1
 A   A   A
 GT  A   A   GT
 A   A   A   A   A
end
```

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More on Geometry



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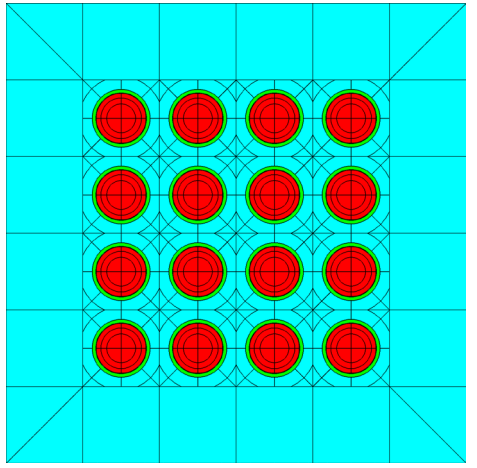
hgap

```
=polaris_6.3
title "W17x17"
lib "broad_n"
%---------------------------------------%
% geometry
%---------------------------------------%
geom W17 : ASSM 4 1.26
hgap 1.26 : COOL.1
%---------------------------------------%
% comps and mats
%---------------------------------------%
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26 600
mat GAP.1  : FILLGAS temp=600
mat CLAD.1 : ZIRC4   temp=600
comp WATER : LW 1300
mat COOL.1 : WATER 0.661 600
%---------------------------------------%
% pins and mesh
%---------------------------------------%
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP.1 CLAD.1 COOL.1
mesh FUEL : nr=3 ns= 4
mesh COOL : nr=2 ns= 8
end
```

- hgap - optional
  - half distance between adjacent assemblies

```
hgap  [ dE   dN   dW    dS ]
      [: ME  MN   MW   MS ]
```

- d – half distance (cm)
- M – material name
- 1, 2, 4 values are acceptable
  - 1: same values for all 4 faces (PWR)
  - 2: East=South and North=West (BWR)
  - 4: general case, all four sides can be different



```
=polaris_6.3
title "W17x17"
lib "broad_n"
%-------------------------------------%
% geometry
%-------------------------------------%
geom W17 : ASSM 4 1.26
hgap 1.26 0.61 : COOL.1 MOD.1
%-------------------------------------%
% comps and mats
%-------------------------------------%
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26 600
mat GAP.1  : FILLGAS temp=600
mat CLAD.1 : ZIRC4   temp=600
comp WATER : LW 1300
mat COOL.1 : WATER 0.661 600
mat MOD.1 : WATER 0.661 600
%-------------------------------------%
% pins and mesh
%-------------------------------------%
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP.1 CLAD.1 COOL.1
mesh FUEL : nr=3 ns= 4
mesh COOL : nr=2 ns= 8 nf=2 nd=3
mesh MOD  :            nf=3 nd=2
end

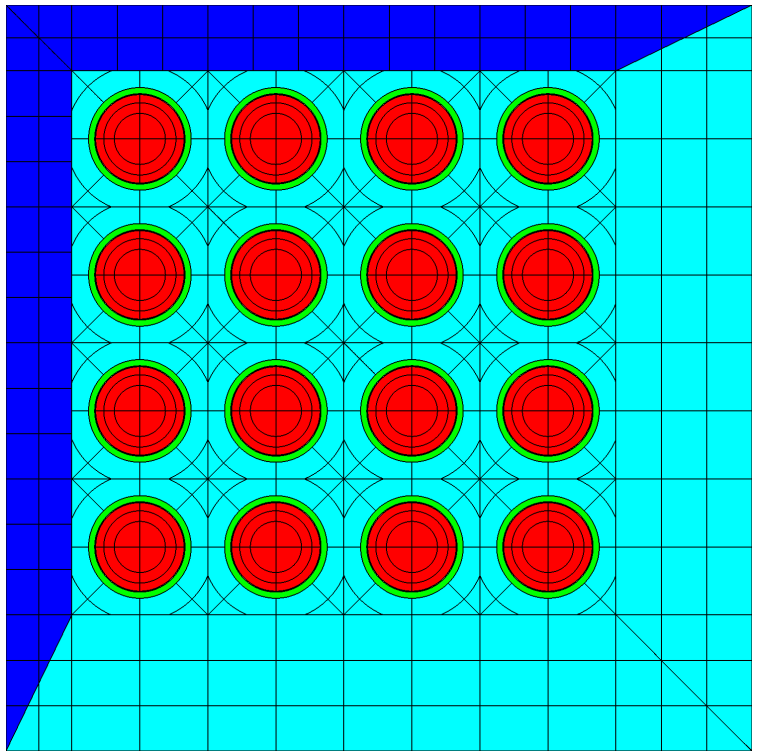
```

Adjusting mesh in non-fuel region

mesh MCLASS|MNAME : [nr=Int] [ns=Int] [nf=Int] [nd=Int]

nf – number of faces per pin, default 2

nd – number of divisions per pin, default 1



channel

```
=polaris_6.3
title "W17x17"
lib "broad_n"
%---------------------------------
% geometry
%---------------------------------
geom W17 : ASSM 17 1.26
hgap 0.04 : COOL.1
%---------------------------------
% comps and mats
%---------------------------------
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26 600
mat GAP.1  : FILLGAS temp=600
mat CLAD.1 : ZIRC4   temp=600
mat TUBE.1 : ZIRC4   temp=600
comp WATER : LW 1300
mat COOL.1 : WATER 0.661 600
mat MOD.1  : WATER 0.661 600
%---------------------------------
% pins and mesh
%---------------------------------
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP.1 CLAD.1 COOL.1
pin I : 0.559 0.605
      : MOD.1 TUBE.1 COOL.1
pin G : 0.561 0.602
      : MOD.1 TUBE.1 COOL.1
mesh COOL : nr=2 ns= 8
mesh FUEL : nr=3 ns= 8
```

```
=polaris_6.3
title "W17x17"
lib "broad_n"
%---------------------------------
% geometry
%---------------------------------
geom W17 : ASSM 17 1.26
hgap 0.04 : COOL.1
channel COOL
%---------------------------------
% comps and mats
%---------------------------------
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26 600
mat GAP.1  : FILLGAS temp=600
mat CLAD.1 : ZIRC4   temp=600
mat TUBE.1 : ZIRC4   temp=600
comp WATER : LW 1300
mat COOL.1 : WATER 0.661 600
mat MOD.1  : WATER 0.661 600
%---------------------------------
% pins and mesh
%---------------------------------
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP.1 CLAD.1
pin I : 0.559 0.605 : MOD.1 TUBE.1
pin G : 0.561 0.602 : MOD.1 TUBE.1
mesh COOL : nr=2 ns= 8
mesh FUEL : nr=3 ns= 8

```

- channel – defines material for outermost pin region

channel [Mchan=MCLASS]

- Mchan – material class: the 1st part of the mat name
- The actual material used in the outermost pin region is the first sorted material with matching class, typically COOL.1

modeling oversized pins

```
=polaris_6.3
lib "broad_n"
%---------------------------------------%
% geometry
%---------------------------------------%
geom fake : ASSM 3 1.26
channel COOL
%---------------------------------------%
% comps and mats
%---------------------------------------%
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26 600
mat GAP.1  : FILLGAS temp=600
mat CLAD.1 : ZIRC4   temp=600
comp WATER : LW 1300
mat COOL.1 : WATER 0.661 600
%---------------------------------------%
% pins
%---------------------------------------%
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP   CLAD
pin X size=2 : 1.0 1.1 : FUEL.1 CLAD

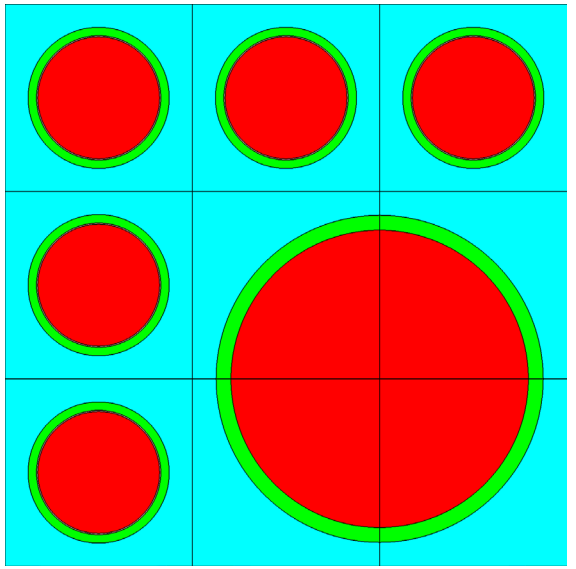
  % equivalent to

pin X 2 : 1.0 1.1 : FUEL.1 CLAD
pinmap F F F
       F X X
       F X X
end
```

pin PINID [size=Real]

: r1 r2 … ri … rN
: M1 M2 … Mi … MN [Mout]

- size=1 is default.
- size=2 creates 2x2 pin cell



BWR Geometry Basics

A. lattice pitch

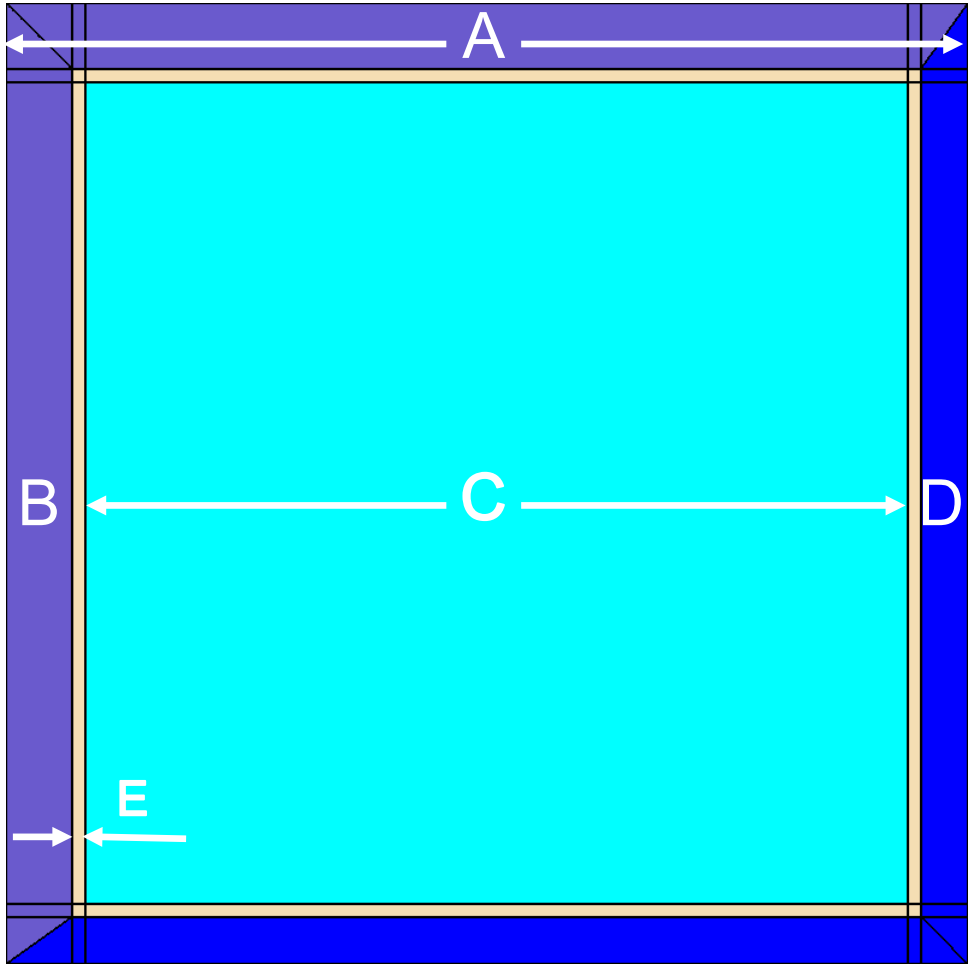
B. wide gap (north and west sides)

C. in-channel span

D. narrow gap (east and south sides)

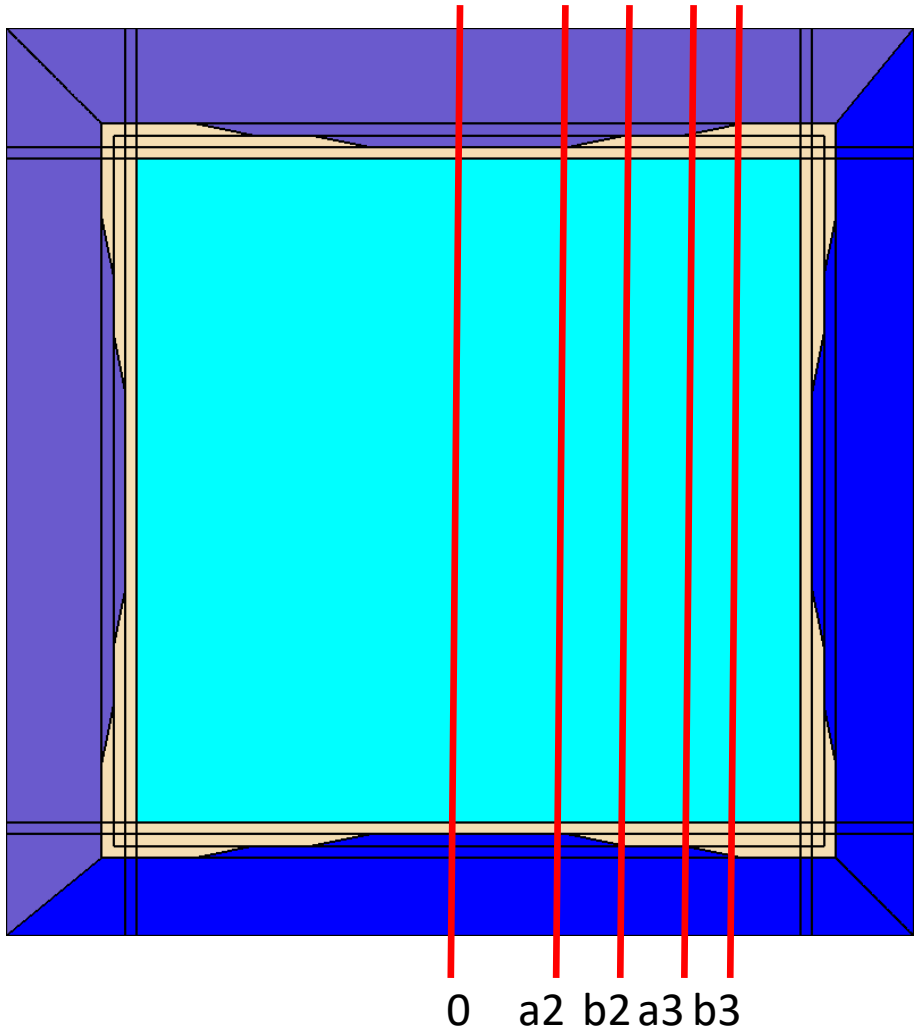
E. channel box thickness

- Must know 4 out of 5 from design documentation
- The 5th value is computed from A=B+C+D+2E
- Control blades are inserted into the wide gaps
- Detectors are inserted into the narrow gaps
- Typical values:
  - lattice pitch: 15.24 cm
  - channel box thickness: 80 mil (0.2032 cm)



$$A = B + C + D + 2E$$

box



- single region channel box definition

box thick=Real [rad=Real] [hspan=Real] [Mbox=MNAME]

- multiregion channel box definition

box thick=Real [rad=Real] [hspan=Real] [Mbox=MNAME]
[: t2 t3 … tN]
[: a2 a3 … aN]
[: b2 b3 … bN]

- **t2 t3 … tN** – channel box thickness for region 2, 3, … N
- regions 2 through N can have “cutout” regions (cm)
- **a2 a3 … aN** – distance from centerline to bottom of cutout region 2, 3, … N (cm)
- **b2 b3 … bN** – distance from centerline to top of cutout region 2, 3, … N (cm)

box

box thick=Real [rad=Real] [hspan=Real] [Mbox=MNAME]

```
=polaris
%-------------------------------------%
% general options
%-------------------------------------%
title "BWR 7x7"
lib "broad_n"
system BWR
%-------------------------------------%
% geometry (lattice pitch=15.24)
%-------------------------------------%
geom bwr7x7 : ASSM 7 1.88
hgap 0.47498 0.9525 : MOD.1 MOD.2

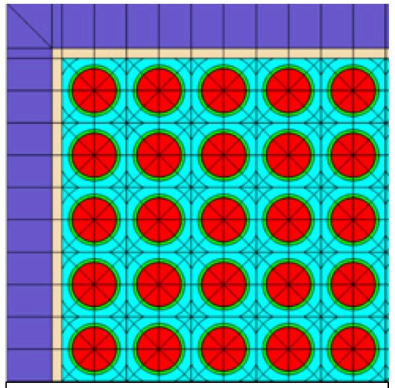
box   0.2032 0.0 6.70306

      %equivalent to

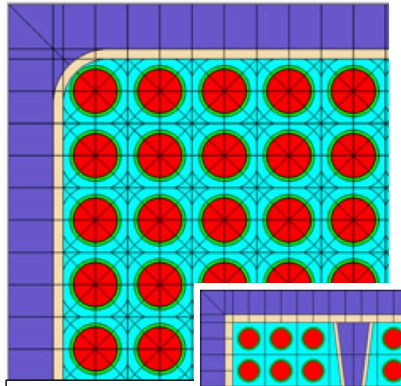
box   thick=0.2032
      rad=0.0
      hspan=6.70306
      MBox=CAN.1

      %equivalent to

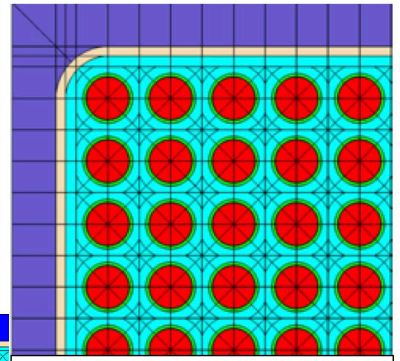
box   0.2032 hspan=6.70306
```



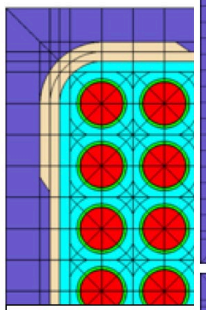
```
box 0.2
```



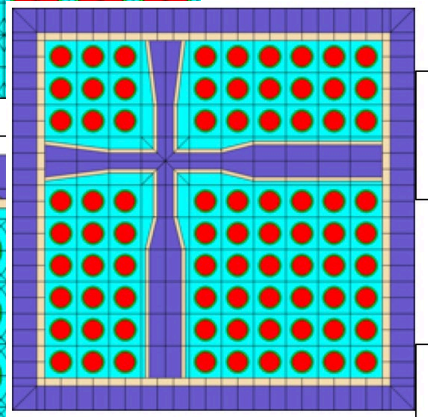
```
box 0.2 0.9
```



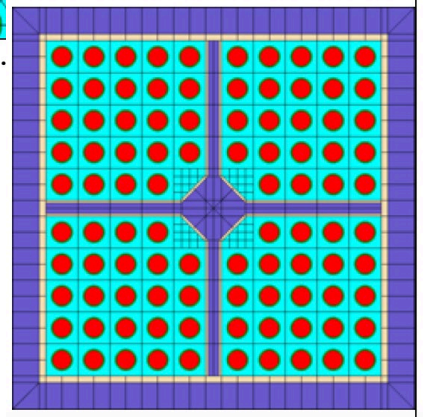
```
%default hspan = 6.475 cm
box 0.2 0.9 6.7
```



```
box 0.2 0.9 6.
    : 0.2
    : 4.0
    : 4.3
```



```
geom manual_ex : ASSM 9 2.0
hgap 1.5
box 0.5 0.0 10.5
cross 1.5 0.25 row=3 : 0 4  11 13 21
                     : 1 .5 .5 1  1
```



```
geom svea : ASSM 10 1.2
hgap 1.0
box 0.252
cross 0.3 0.1
   : .0 5.1 6.3 7.5 12.6
   : 0.2 0.2 1.4 0.2 0.2
%fuel pin
pin 1 : 0.35 0.4 : FUEL.1 CLAD.1
%empty pin
pin E : 0.6 : COOL.1 : SQR
mesh COOL.1 nx=4 ny=4
pinmap
1
1 1
1 1 1
1 1 1 1
1 1 1 1 E
1 1 1 1 E E
1 1 1 1 1 1 1
1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
```

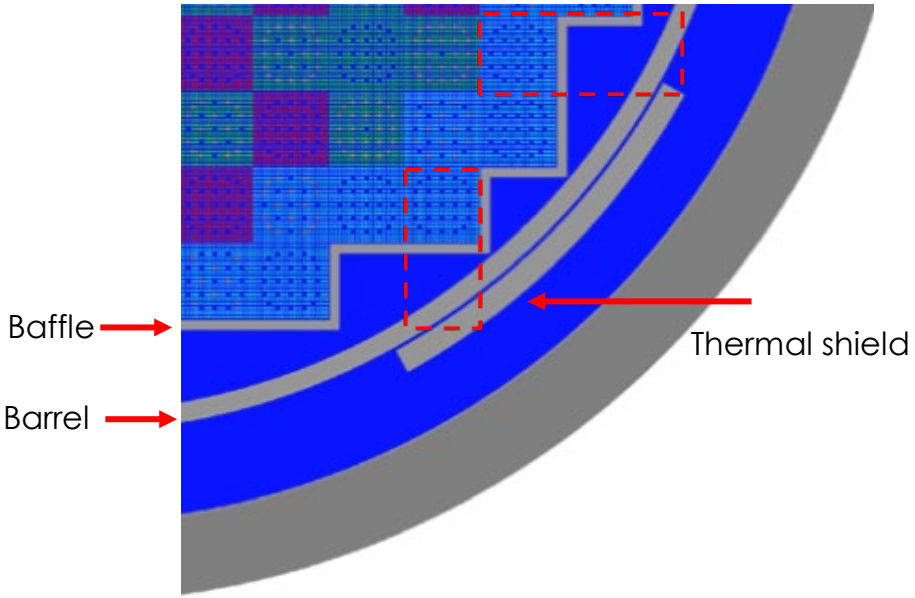

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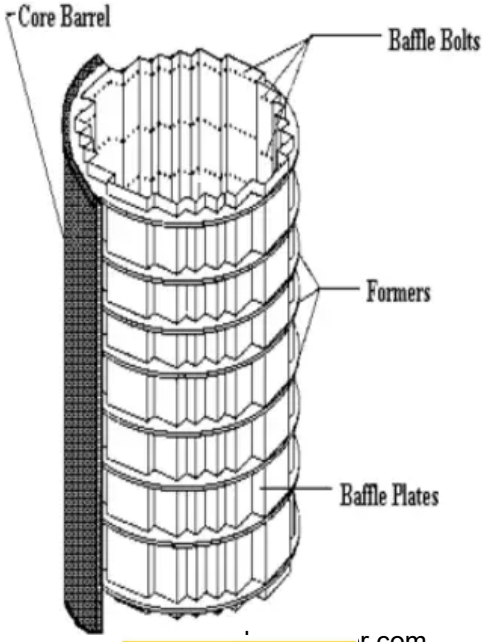


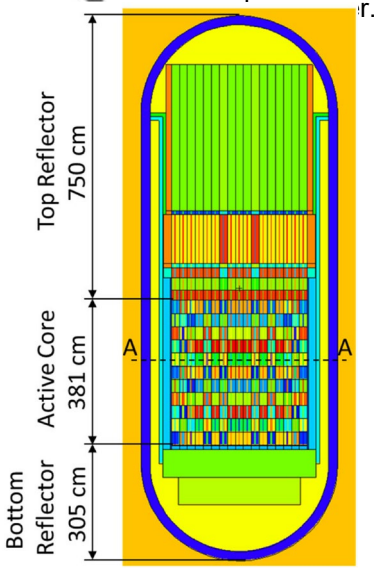
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Reflector modeling

- Core analysis generally requires top, bottom, radial reflector model
- No history or branches required
  - if any: coolant dens, temp, boron
- Requires knowledge of core structure geometry dimensions and material properties for core structure
  - Baffle, rod end plugs, upper plenum region, end spacer grids, upper/lower core plate
- Typical radial reflector:
  - Fuel: low enriched fuel
  - Slab zones:
    1. small gap b/w fuel and baffle
    2. baffle
    3. coolant
  - Reflector width ~ lattice pitch





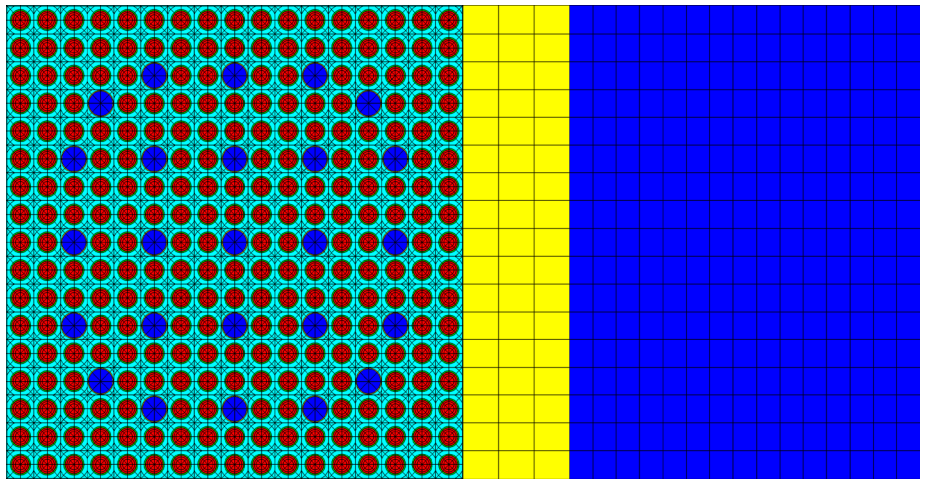


Detection of Numerical Power Shift Anomalies in Burnup Modeling of a PWR Reactor
https://doi.org/10.3390/su15043373

SCALE 6.3.1 last revision (May 2024)

reflector

```
=polaris_6.3
%-------------------------------------%
% general options
%-------------------------------------%
title "W17x17 REFL"  "Polaris training"
lib "broad_n"
system PWR
%-------------------------------------%
% geometry
%-------------------------------------%
geom W17 : ASSM 17 1.26
hgap 0.04
geom radref : REFL 21.5
slab : 5          16.5
     : TUBE       MOD.1
     : 3          15
```



- geom card for reflector

geom GNAME : REFL thick=REAL

- GNAME – reflector name
- REFL – indicates reflector geometry
- thick – total reflector thickness (cm)
- geom ASSM card must have sym=FULL

- slab – defines a series of slabs for reflector

slab [SLABID]
: t1 t2 … ti … tN
: M1 M2 … Mi … MN
[: nx1 nx2 … nxi … nxN]
[: ny1 ny2 … nyi … nyN]

- SLABID – slab identifier, default is REFL GNAME
- t_i – slab thickness (cm)
- M_i – slab material
- nx_i – # of x-mesh
- ny_i – # of y-mesh
- Polaris preserves the horizontal planar pin boundaries of the fuel assembly … ny is not necessary

Exercise #3

Start with w17x17.inp

- radref.inp
- remove SE symmetry
- reduce enrichment to 1.0%
- reduce COOL and MOD boron to 700 ppm
- slabs (21.5 cm total)
  - 0.19 cm gap b/w fuel and baffle (COOL.1)
  - 2.85 cm baffle SS304 (TUBE)
  - remainder MOD.1
  - # of x-mesh: ceiling(thick/ppitch)= (1,3,15)

- botref.inp
- remove SE symmetry
- reduce COOL and MOD boron to 700 ppm
- slabs (21.5 cm total)
  - 10.75 cm slab 50% wt zirc4 and 50% wt 700 ppm WATER, 1.2 g/cc
  - 10.75 cm slab 80% wt ss304, 20% wt 700 ppm WATER, 2.1 g/cc
  - # of x-mesh: ceil(t/pin_pitch)

- topref.inp
- remove SE symmetry
- reduce COOL and MOD boron to 700 ppm
- slabs (21.5 cm total)
  - 10.75 cm slab 65% wt zirc4 and 35% wt 700 ppm WATER, 1.0 g/cc
  - 10.75 cm slab 80% wt ss304, 20% wt 700 ppm WATER, 2.3 g/cc
  - # of x-mesh: ceil(t/pin_pitch)



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system PWR

Material	Composition	Plot Color	Additional info
Unless noted otherwise, T=565K, nr=1, ns=8, nf=2, nd=1			
COOL.1	H2O	cyan	pin coolant material, nr=2
COOL.2	H2O	aquamarine	use for large guide tubes with user-defined mesh
MOD.1	H2O	blue	optional, use for inner guide tube material
Water materials initialized to boron = 0 ppm, density = 0.743 g/cc			
FUEL.1	n/a	red	depletable (deplete), auto-expanded (shield)
BP.1	n/a	n/a	depletable (deplete), auto-expanded (shield)
CNTL.1	AIC	pink	auto-expanded (shield)
CNTL.2	B4C	cadetblue	auto-expanded (shield)
CLAD.1	ZIRC4	lime	
TUBE.1	ZIRC4	yellow	optional for guide tubes
GAP.1	FILLGAS	rosybrown	
STRUCT.1	SS304	goldenrod	blade sheath/central support material

system PWR before and after

```
=polaris_6.3
title "W17x17"
lib "broad_n"
%---------------------------------------
% geometry
%---------------------------------------
geom W17 : ASSM 17 1.26
hgap 0.04 : COOL.1
channel COOL
%---------------------------------------
% comps and mats
%---------------------------------------
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26 600
mat GAP.1  : FILLGAS temp=600
mat CLAD.1 : ZIRC4   temp=600
mat TUBE.1 : ZIRC4   temp=600
comp WATER : LW 1300
mat COOL.1 : WATER 0.661 600
mat MOD.1  : WATER 0.661 600
%---------------------------------------
% pins and mesh
%---------------------------------------
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP   CLAD
pin I : 0.559 0.605 : MOD.1 TUBE
pin G : 0.561 0.602 : MOD.1 TUBE
mesh COOL : nr=2 ns= 8
mesh FUEL : nr=3 ns= 8

```

```
=polaris_6.3
title "W17x17"
lib "broad_n"
system PWR
%---------------------------------------%
% geometry
%---------------------------------------%
geom W17 : ASSM 17 1.26
hgap 0.04
%---------------------------------------%
% comps and mats
%---------------------------------------%
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26
%---------------------------------------%
% pins and mesh
%---------------------------------------%
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP   CLAD
pin I : 0.559 0.605 : MOD.1 TUBE
pin G : 0.561 0.602 : MOD.1 TUBE
mesh FUEL : nr=3


```

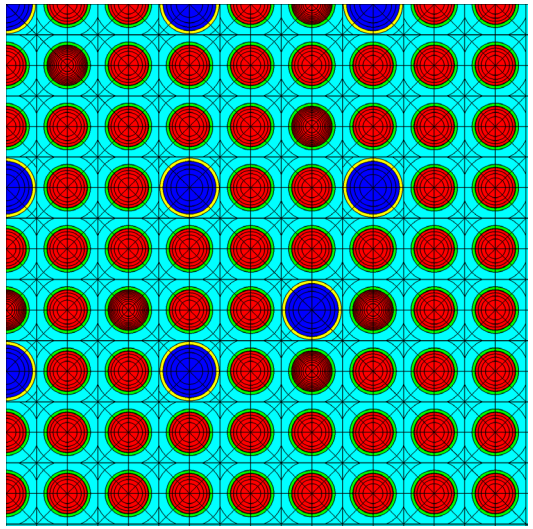
Note: right hand side uses default system temperatures

system BWR

Material	Composition	Plot Color	Additional info
Unless noted otherwise, T=557K, nr=1, ns=8, nf=2, nd=1			
COOL.1	H2O	cyan	pin coolant material, nr=2
COOL.2	H2O	aquamarine	extra pin coolant material
MOD.1	H2O	blue	Wide hgap material, internal moderator for water rods
MOD.2	H2O	purple	Narrow hgap material, extra internal moderator
Water materials initialized to boron = 0 ppm, void=0, liquid_dens= 0.743 g/cc, vapor_dens= 0.0353 g/cc			
FUEL.1	n/a	red	depletable (deplete), auto-expanded (shield)
CAN.1	n/a	n/a	channel box material
CNTL.1	AIC	pink	auto-expanded (shield)
CNTL.2	B4C	cadetblue	auto-expanded (shield)
CLAD.1	ZIRC2	lime	
TUBE.1	ZIRC2	yellow	optional for guide tubes
GAP.1	FILLGAS	rosybrown	
STRUCT.1	SS304	goldenrod	blade sheath/central support material

Exercise #4

- pwr-lattice-system.inp
  - What are the MOD and COOL materials? Their densities and temperatures?
  - Why are there two water materials?
  - Comment the system card, try to fix the input errors.



```
=polaris
%Exercise problem #3 PWR lattice
%Problem 1: What are the MOD and COOL materials?
their densities and temperatures?
%Problem 2: Why are there two water materials?
%Problem 3: Comment the system card try to fix the input
errors.
%    general options
% ---------------------------------------------
title    "Framatome assem lattice enr4.7_24Gd_enr8-
CR000-DC1-PC2-TF2"
lib      "broad_lwr"
% ---------------------------------------------
%    geometry
% ---------------------------------------------
system   PWR
% ---------------------------------------------
%    geometry
% ---------------------------------------------
geom     F17 ASSM 17 1.26 SE
hgap     0.042
opt      ESSM  NumAzim=10
%    compositions and materials
% ---------------------------------------------
% fuel compositions
comp uox350 : UOX enr=3.50
comp uox470 : UOX enr=4.70
comp g800 : WT GD2O3=8.00 uox350=-100
% cladding composition is a user-defined composition
comp m5      : WT
               Nb=1.0
               O=0.125
               Zr=-100
% now adding material specs
mat FUEL.1    : uox470  dens=10.4300
mat GAD.1     : g800  dens=10.0700
mat CLAD.1    : m5  dens=6.5083
mat TUBE.1    : m5  dens=6.4800
%    pins definitions
% ---------------------------------------------
pin A   : 0.4096   0.4180   0.4796
        : FUEL.1   GAP      CLAD.1
pin GD1 : 0.4096   0.4180   0.4796
        : GAD.1    GAP      CLAD.1
pin IT  : 0.5450   0.6120
        : MOD.1    TUBE.1
pin GT  : 0.5450   0.6120
        : MOD.1    TUBE.1
%    meshing options
% ---------------------------------------------
mesh GAP   : ns=1
mesh FUEL  : nr=4
mesh GAD   : nr=10
mesh COOL  : nx=4 ny=4
mesh MOD.1 : nr=4 ns=8
%    maps
% ---------------------------------------------
pinmap
 IT
 A   GD1
 A   A   A
 GT  A   A   GT
 A   A   A   A   A
 GD1 A   GD1 A   A   GT
 GT  A   A   GT  A   GD1 A
 A   A   A   A   A   A   A   A
 A   A   A   A   A   A   A   A   A
 end
```


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state card for changing material properties



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SCALE 6.3.1 last revision (May 2024)

state part 1

```
%-------------------------------------%
% maps
%-------------------------------------%
pinmap
  I
  F F
  F F F
  G F F G
  F F F F F
  F F F F F G
  G F F G F F F
  F F F F F F F F
  F F F F F F F F F
%-------------------------------------%
% state
%-------------------------------------%
state ALL : temp=590
  COOL : dens=0.68 boron=1300
  MOD  : dens=0.71 boron=1300 temp=575
  FUEL : temp=900
  CLAD : temp=700 TUBE : temp=580
end
```

state MNAME|MCLASS : p1=val1 p2=val2 …
MNAME|MCLASS : p1=val1 p2=val2 …
…

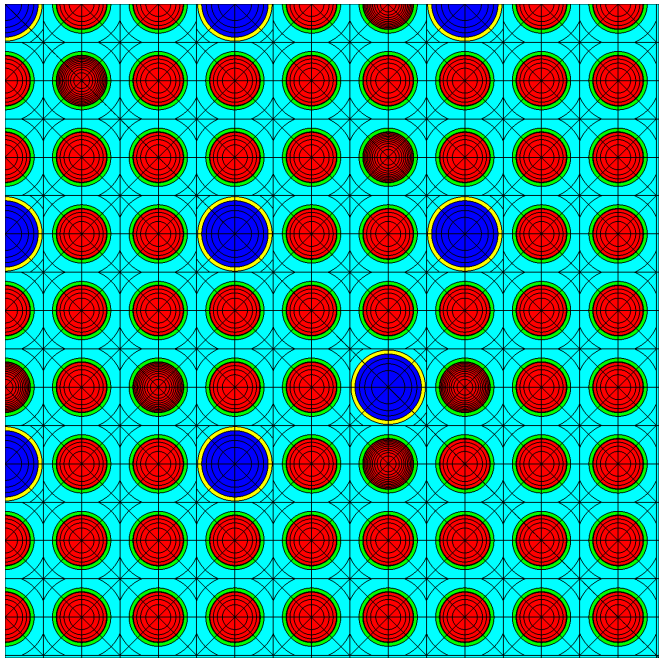
- MNAME or MCLASS – material name (FUEL.1) or material class (FUEL) or ALL can be used to initialize all material properties to same value
- p – property name
  - all materials have dens= and temp= properties
  - system PWR: COOL and MOD have boron= properties
  - system BWR: COOL and MOD have boron= and void= properties
- val – property value

- Whitespace before and after "**:**" is recommended

- It is a good modeling practice to use state card to make sure all materials are specified at correct density/temperature or void fraction/boron

Exercise #5

- pwr-lattice-system-state.inp
  - Fix the state card error and set all fuel materials
    - temp=900 density=10.56
  - Change clad temperature. Material card vs State card?
  - Change fuel temperature, calculate Doppler coefficient



pwr-lattice-system.inp

+

```
state  ALL : temp=563.0
       FUEL : temp=   GAD : temp=  COOL : dens=0.7468 boron= 700.0  MOD : temp=563.0 dens=0.7468 boron= 700.0
```

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insert card control card

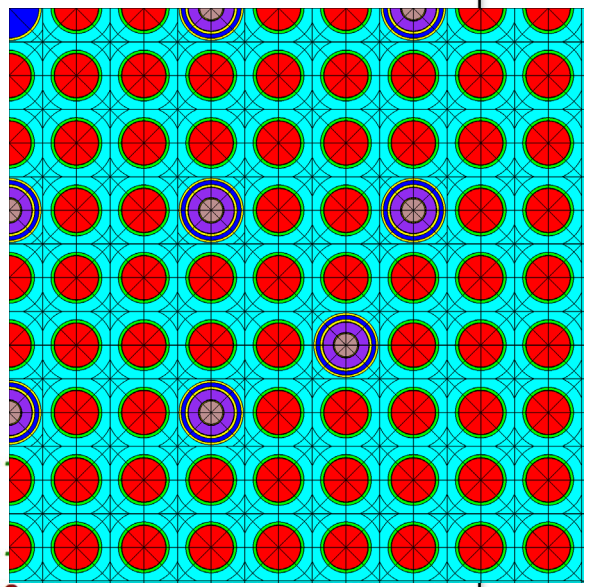


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insert

```
pin G : 0.561 0.602 : MOD.1 TUBE
pinmap
I
F F
F F F
G F F G
F F F F F
F F F F F G
G F F G F F F
F F F F F F F F
F F F F F F F F F
pin P : 0.214 0.231 0.241  0.427
        0.437 0.484 0.561  0.602
      : GAP   TUBE  GAP    BP
        GAP   TUBE  MOD.1  TUBE
insert PYREX_MAP
_
_ _
_ _ _
P   _ _ P
_ _ _ _ _
        P
_ _ _ _ _
P   _ _ P _ _ _
_ _ _ _ _ _ _ _
_ _ _ _ _ _ _ _ _
%--------------------
% state
%--------------------
state ALL   : temp=590
 PYREX MAP : in=yes
```



- insert – define set of "inserts"--typically loaded in at BOC and removed after first cycle, e.g. WABA

insert INAME: $PINID_1$ $PINID_2$ … $PINID_i$ … $PINID_N$

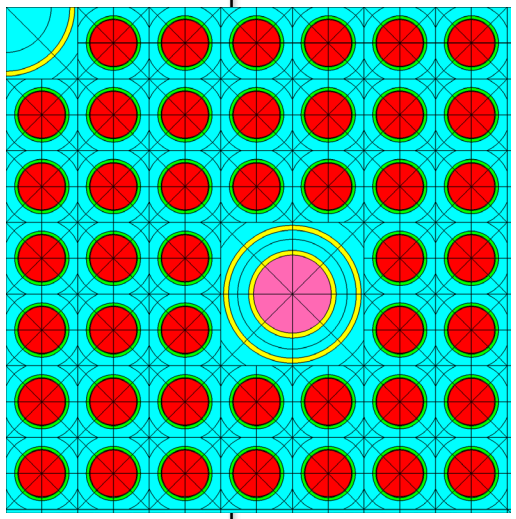
- INAME – name of insert map
- "_" indicates a map location without an insert
- Must include enclosing guide tube
- inserts are inserted into the problem geometry using state or branch cards

state INAME : in=*Bool*

- INAME – the name of the map
- in=yes|true – map is inserted
- in=no|false – map is not inserted

control

```
31 pin W 2 : 1.314 1.416 : COOL.1 TUBE
32 pin C 2 : 0.8    0.9  1.314  1.416
33         : CNTL.1 TUBE COOL.1 TUBE
34
35 pinmap
36  W
37  F F
38  F F F
39  F F F W
40  F F F W W
41  F F F F F F
42  F F F F F F F
43
44 control CR_MAP : RODLET
45  _
46  _ _
47  _ _ _
48  _ _ _ C
49  _ _ _ C C
50  _ _ _
51  _ _ _ _ _ _
52  _ _ _ _ _ _ _
53 state ALL : temp=570
54   CR_MAP : in=yes
55      FUEL : temp=997
56      COOL : dens=0.7307 boron=663
57
58
59
60
```



- control – define a control rod/blade structure

control ENAME: RODLET $PINID_1$ $PINID_2$ … $PINID_i$ … $PINID_N$

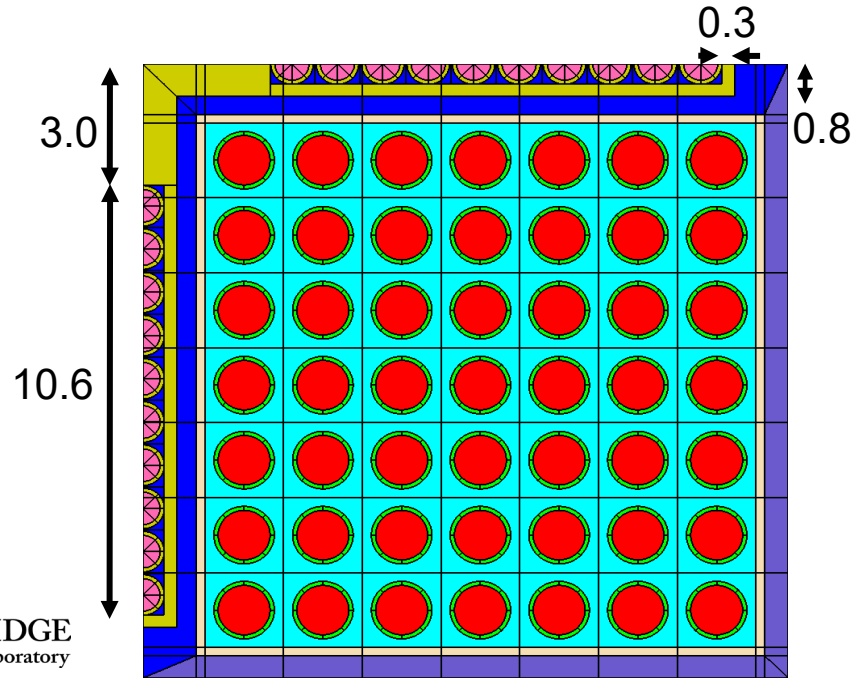
- RODLET indicates rod-type control map
- inserts are inserted into the problem geometry using state or branch cards

state ENAME : in=*Bool*

- ENAME – the name of the control structure
- in=yes|true – structure is inserted
- in=no|false – structure is not inserted

blade

```
16 comp c_e293 : UOX 2.93
17 mat  FUEL.1 : c_e293 10.32
18 %---------------------------------------%
19 % control blade
20 %---------------------------------------%
21 pin B : 0.4 0.5
22       : CNTL.1 STRUCT.1 MOD.1
23 control blade1 : BLADE 0.8 0.3 3.0
24                : B
25                : 10.6
26                : 10
27 state blade1 : in=yes
28
```

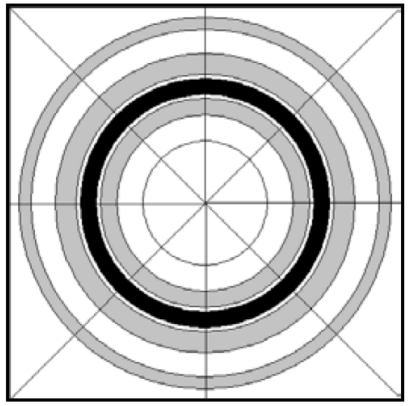


control : BLADE
  hwgthck=Real sththck=Real cslnth=Real
  : ID_1 ID_2 … ID_N
  : L_1 L_2 … L_N
  : N_1 N_2 … N_N

- hwgthck – half blade wing thickness (cm)
  - required, must be > 0
- sththck – blade sheath thickness (cm)
  - required, must be >= 0
- cslnth – central support length (cm)
  - required, must be >= hwgthck
- ID_i – PINID or SLABID for section i
- L_i – length of section i (cm)
- N_i – number of pins or slab regions in section i

Table 13: WABA Rod Specification

Input	Value
Poison Material	B_4C-Al_2O_3
Boron-10 Loading	6.03 mg/cm
Poison Density	3.65 g/cc
Inner Clad Inner Radius	0.286 cm
Inner Clad Outer Radius	0.339 cm
Poison Inner Radius	0.353 cm
Poison Outer Radius	0.404 cm
Cladding Inner Radius	0.418 cm
Cladding Outer Radius	0.484 cm
Annulus Material	Moderator
Cladding Material	Zircaloy-4
Plenum/Gap Material	Helium



- Copy w17x17_rev3.inp as w17x17_waba.inp
- Create WABA **comp** (WABA), **mat** (BP.1), **pin** (W), and **insert** map (WABA_MAP all 24 GT locations)
- Create PYREX **mat** (BP.2), **pin** (P), and **insert** map (PYREX_MAP all 24 GT locations)
- Create AIC control rod **pin** (A), and **control** map (AIC_MAP all 24 GT locations)
- Create B4C control rod **pin** (B), and **control** map (B4C_MAP all 24 GT locations)
- Insert WABAs, compute k-eff, proceed next slide

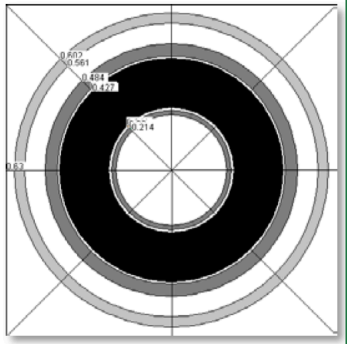
Hint: these data imply B4C is 9.49 wt%

Table 8: RCCA Rod and Drive Specification

Input	AIC	B_4C
Composition	80/15/5% Ag/In/Cd (Lower)	100% B_4C (Upper)
Poison Density	10.2 g/cc	1.76 g/cc
Poison Radius	0.382 cm	0.373 cm
Poison Height	101.6 cm	259.08 cm
Cladding Inner Radius	0.386 cm	
Cladding Outer Radius	0.484 cm	
Total Poison Height	360.68 cm	
Axial Location of Poison (when fully inserted)	17.031 cm	
Plenum Height above Poison	10.7 cm	
End Plug Height	≈ 1.9 cm	
Step Size	1.5875 cm	
Maximum number of steps	230	
Cladding Material	SS304	
Plenum Material	Helium	

Table 6: Pyrex Rod Specification

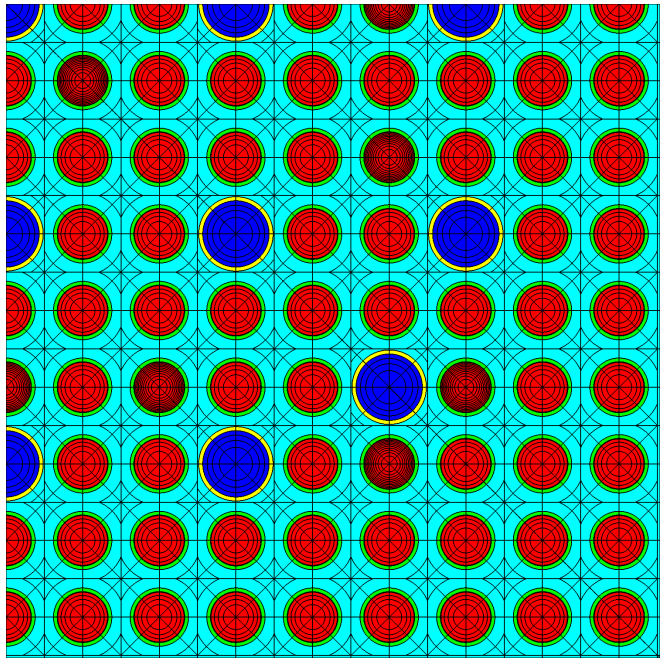
Input	Value
Enrichment	12.5 wt% B_2O_3
Boron-10 Loading	6.24 mg/cm
Pyrex Density	2.25 g/cc
Inner Tube Inner Radius	0.214 cm
Inner Tube Outer Radius	0.231 cm
Pyrex Inner Radius	0.241 cm
Pyrex Outer Radius	0.427 cm
Cladding Inner Radius	0.437 cm
Cladding Outer Radius	0.484 cm
Poison Height	360.68 cm
Plenum Height above Poison	22.2 cm
Axial Location of Poison	15.761 cm
End Plug Height	≈ 2.54 cm
Inner Tube Material	SS304
Plenum Material	Helium
Cladding Material	SS304



Reference: CASL Benchmark for WBN1

Exercise #6

- pwr-lattice-system-state.inp
  - Fix the sate card error and set all fuel material
    - temp=900 density=10.56
  - Change clad temperature. Material card vs state card?
  - Change fuel temperature, calculate Doppler coefficient



Exercise #7

- pwr-lattice-system-state-cr.inp
  - Fix the input file
    - Control rod is made of AIC (0.4330 cm radius) with a SS clad
  - Insert control rod and calculate rod worth
  - Why are there two MOD materials?
  - Can you make it work without specifying control element?
  - Can you calculate rod worth without using Rodlet?
  - Is B4C or AIC worth higher?
  - Insert WABA to all GT locations

```
=polaris
title    "Framatome assem lattice enr4.7_24Gd_enr8"
lib      "broad_lwr"
system   PWR
geom     F17 ASSM 17 1.26 SE
hgap     0.042
opt      ESSM  NumAzim=10
% fuel compositions
comp uox350 : UOX enr=3.50
comp uox470 : UOX enr=4.70
comp g800 : WT GD2O3=8.00 uox350=-100
% cladding composition is a user-defined
comp m5      : WT
 Nb=1.0
             O=0.125
             Zr=-100
% now adding material specs
mat FUEL.1    : uox470  dens=10.4300
mat GAD.1     : g800  dens=10.0700
mat CLAD.1    : m5  dens=6.5083
mat TUBE.1    : m5  dens=6.4800
pin A   : 0.4096   0.4180   0.4796
       : FUEL.1   GAP      CLAD.1
pin GD1 : 0.4096   0.4180   0.4796
       : GAD.1    GAP      CLAD.1
pin IT  : 0.5450   0.6120
       : MOD.1    TUBE.1
pin GT  : 0.5450   0.6120
       : MOD.1    TUBE.1
pin CR1 :    0.4370   0.4840   0.5450   0.6120
       : CNTL.2   GAP      STRUCT.1 MOD.2
TUBE.1
```

```
%    meshing options
mesh GAP   : ns=1
mesh FUEL  : nr=4
mesh GAD   : nr=10
mesh COOL  : nx=4 ny=4
mesh MOD.1 : nr=4 ns=8
mesh MOD.2 : nr=1 ns=8
%    maps
pinmap
 IT
 A   GD1
 A   A   A
 GT  A   A   GT
 A   A   A   A   A
 GD1 A   GD1 A   A   GT
 GT  A   A   GT  A   GD1 A
 A   A   A   A   A   A   A   A
 A   A   A   A   A   A   A   A   A
control Con : RODLET
 IT
 _   _
 _   _   _
 CR1 _   _   CR1
 _   _   _   _   _
 _   _   _   _   _   CR1
 CR1 _   _   CR1 _   _   _
 _   _   _   _   _   _   _   _
 _   _   _   _   _   _   _   _   _
state  ALL : temp=563.0
FUEL : temp= 900.0 dens=10.56
GAD : temp= 900.0 dens=10.56
COOL : dens=0.7468 boron= 700.0
MOD : temp=563.0 dens=0.7468 boron= 700.0
end
```

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Depletion

bu, bui, dbu cards
t, ti, dti cards
deplete card



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Depletion Methodology

- Polaris uses predictor-corrector depletion:
  - burnup step [bu, bu+dbu]:
    1. flux calculation at bu
    2. deplete (predictor step)
    3. flux calculation at bu+dbu
    4. re-deplete with new flux (corrector step)
    5. average nuclide inventory at bu+dbu from step 2. and step 4.
  - decay step [t, t+dt]:
    1. flux calculation at t
    2. decay calculation to t+dt

Depletion

```
31 %-------------------------------------%
32 % maps
33 %-------------------------------------%
34 pinmap
35 I
36 F F
37 F F F
38 G F F G
39 F F F F F
40 F F F F F G
41 G F F G F F F
42 F F F F F F F F
43 F F F F F F F F F
44 %-------------------------------------%
45 % state
46 %-------------------------------------%
47 pow 40
48 bu 0 4 8 12 %burnup 0 is optional
49
50    %equivalent to
51
52 pow  40   40    40
53 bu 4000 8000 12000 : MWD/MTIHM
54
55    %equivalent to
56
57 pow   40  40  40
58 t   0 100 200 300  %time 0 is optional
59
60
```

pow(er) p1 … pi … pN

bu b1 … bi … bN [:units=GWD/MTIHM|MWD/MTIHM]

t t1 … ti … tN [:units=SECONDS|MINUTES|HOURS|DAYS|YEARS]

- power is required (units are MW/MTIHM)
- bu vs t
  - user preference
  - t is required for decay steps
  - t=0 or bu=0 is optional
- Example 1, Constant power:
  - only 1 power value is needed, but multiple values are accepted
  - multiple power values: requires same number of bu (or t) values (ignoring the initial 0 value)

Depletion

```
%-------------------------------------%
% maps
%-------------------------------------%
pinmap
I
F F
F F F
G F F G
F F F F F
F F F F F G
G F F G F F F
F F F F F F F F
F F F F F F F F F
%-------------------------------------%
% state
%-------------------------------------%
pow 40  35  30  0
t   100 200 300 330

   %equivalent to

pow 40  35  30  0
dt  100 100 100 330

   %equivalent to

pow  40   35   30   0
dt 2400 2400 2400 720 : HOURS
```

dbu b1 … bi … bN [: units=GWD/MTIHM|MWD/MTIHM]

dt t1 … ti … tN [:units=SECONDS|MINUTES|HOURS|DAYS|YEARS]

- dbu and dt do not support an initial 0 value
- multiple power values: requires same number of dbu (or dt) values
- Example 2, Power history:
  - time-based input is required because of decay steps

history example

```
=polaris_6.3
lib "broad_n"
sys PWR
geom taka : ASSM 1 1.26
comp u411 : UOX 4.11
mat FUEL.1 : u411 10.412
pin 1 : .4025  .475  : FUEL.1 CLAD
state ALL  : temp=600
       COOL : dens=0.6 boron=1100
       FUEL : temp=900
read history
%---------------------------------------%
% cycle 1
%---------------------------------------%
pow 39
state COOL : boron=900 850 700 600 400
       FUEL :  temp=900 910 920 890 880
dt                    50  50 100 100 200
pow 0
ti 70
%---------------------------------------%
% cycle 2
%---------------------------------------%
pow                   42  41  38  39  37
state COOL : boron=900 850 700 600 300
dt                    50  50  50 100 250
pow 0
ti 80
end history
end
```

- history block allows for time-dependent operational changes
- similar to TIMETABLE block in TRITON
- outside of history block
  - one state card to initialize state variables

- inside history block
  - power, state, and burnup/time cards are entered together
    - power – single value or array
    - state – array
    - burnup/time – array
    - all arrays must be same size
    - state must precede burnup/time
  - multiple power/state/time cards may be stacked together
- convenient for RCA benchmarks

deplete

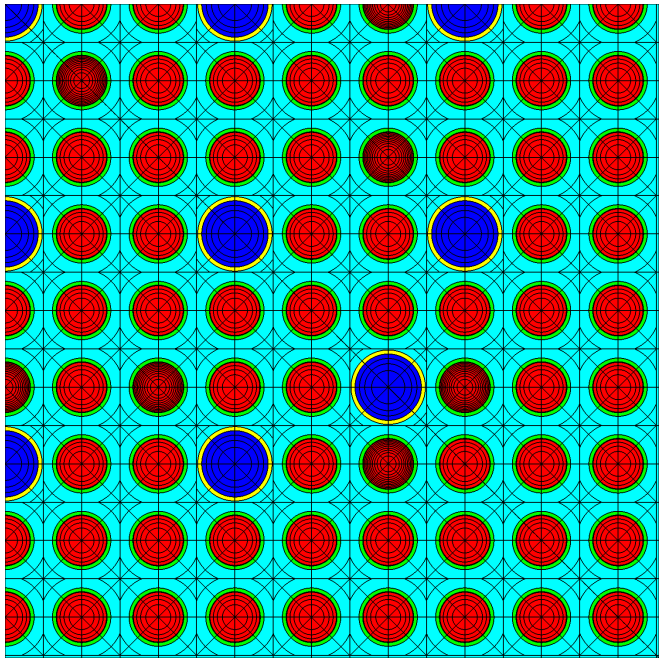
```
31 %-------------------------------------%
32 % maps
33 %-------------------------------------%
34 pinmap
35 I
36 F F
37 F F F
38 G F F G
39 F F F F F
40 F F F F F G
41 G F F G F F F
42 F F F F F F F F
43 F F F F F F F F F
44 %-------------------------------------%
45 % state
46 %-------------------------------------%
47 pow 40
48 bu 4 8 12
49 deplete ALL=no FUEL=yes CLAD=yes
50 state ALL  : temp=590
51       COOL : dens=0.68
52              boron=1300
53       MOD  : dens=0.71
54              boron=1300
55              temp=575
56       FUEL : temp=900
57       CLAD : temp=700
58       TUBE : temp=580
59 end
60
```

deplete M_1=yes|no M_2=yes|no … M_i=yes|no … M_N= yes|no

- M_i – material name or material class
  - yes – material is depleted
  - no – material is depleted
- system PWR defaults
  - deplete ALL=no FUEL=yes BP=yes
- system BWR defaults
  - deplete ALL=no FUEL=yes
- the ALL=no disables all the materials before explicit materials are enabled

Exercise #8

- pwr-lattice-system-state-cr.inp
  - Deplete the fuel lattice (pick any burnup card)
    - 12GWd/MTU burnup in 250 days, using 1GWd/MTU intervals, then cool for 30 days
  - Check if FUEL and GAD materials are being burned. How about WABA? Fix the input.



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Lattice Physics branch card



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SCALE 6.3.1 last revision (May 2024)

Lattice Physics

- 2-step (nodal) core simulator needs few-group cross sections at each ”node” (calculation mesh) based on the node state during the simulation:
  - Fuel temperature
  - Coolant temperature
  - Coolant density
  - Boron concentration
  - Control rod/blade insertion
- Node Dimension:
  - BWR: assembly width (x,y) x 6” (z)
  - PWR: ¼ assembly width (x,y) x 6”(z)
- Each nodal simulator has its own logic to interpolate the cross sections

- Lattice Physics: generate enough few-group cross sections for state-point interpolation by core simulators
  - Require **branch** calculations
    - instantaneous change in state variable at a given burnup
  - Requires **history** calculations
    - BWR fuel depleted at 0% void vs 40% void at constant power
  - Requires **reflector** calculations
- 1000s of state-point calculations are required per core calculation

Branching

```
52 %---------------------------------------%
53 % state
54 %---------------------------------------%
55 %HFP as base state
56 state ALL   : temp=600
57       FUEL  : temp=900
58       COOL  : dens=0.7 boron=600
59 read branch simple
60   %branch 1 - high TF
61   add FUEL : temp=1200
62   %branch 2 and 3 - low/high PC
63   add COOL : boron=0 1500
64   %branch 4 AIC insertion
65   add AIC_MAP : in=yes
66 end branch
67 opt PRINT Xfile16=yes
68 end
69
```

- read branch BNAME/end branch – encloses a set of "instantaneous" state changes
  - BNAME – name of the branch set
- add card
  - material state branch
- add MCLASS/MNAME : prop=X Y Z
  - control or insert state branch
  - add INAME : in=true|false or
  - add INAME : in=yes|no
- FG XS file for PARCS
  - opt PRINT XFile16=yes creates the binary FG XS file for PARCS
  - the text FG XS file for PARCS (T16) is generated by default
  - Polaris skips branches that are identical to nominal state

Branching

```
52 %-------------------------------------%
53 % state
54 %-------------------------------------%
55 %HFP as base state
56 state ALL   : temp=600
57       FUEL : temp=900
58       COOL : dens=0.7 boron=600
59    AIC_MAP : in=no
60
61 read branch cr
62   add AIC_MAP : in=yes
63 end branch
64
65 read branch cobranch
66   %syncronize changes to DC, TC, and CR
67   add COOL : dens=0.6 temp=630 AIC_MAP : in=no
68   add COOL : dens=0.8 temp=570 AIC_MAP : in=no
69   add COOL : dens=0.6 temp=630 AIC_MAP : in=yes
70   add COOL : dens=0.8 temp=570 AIC_MAP : in=es
71
72      % equivalent to
73
74   add COOL : dens=0.6 0.8 0.6 0.8
75              temp=630 570 630 570
76    AIC_MAP : in= no  no yes yes
77 end branch
78 pow 40 bu 1 2
79 opt PRINT Xfile16=yes
80 end
```

- Multiple branch blocks are allowed
  - convenient to organize branches
- Branch definitions can perturb multiple state properties at the same time
- Two approaches to define a table of branch calculations
  1. row represents a branch, columns represent the state properties
  2. row represents the state properties, columns represent a branch

Polaris calculation order:

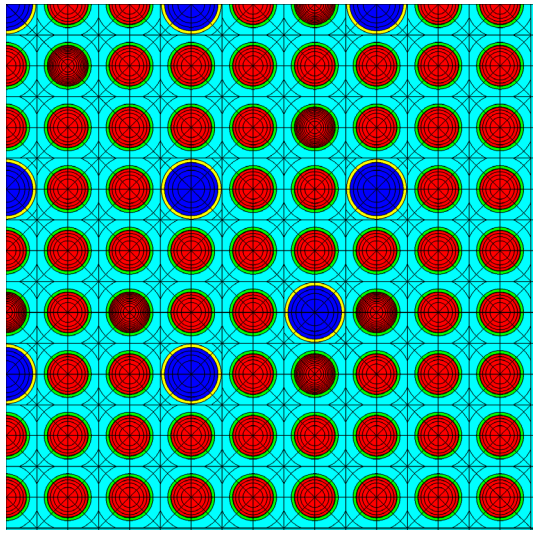
Nominal state, Bu=0
Nominal state, Bu=1
Nominal state, Bu=2
Branch 1 … 5, Bu=0
Branch 1 … 5, Bu=1
Branch 1 … 5, Bu=2

T16 order:

Nominal state, Bu=0
Branch 1 … 5, Bu=0
Nominal state, Bu=1
Branch 1 … 5, Bu=1
Nominal state, Bu=2
Branch 1 … 5, Bu=2

Exercise #9

- pwr-lattice-system-state-cr-branch.inp
  - Check T16 file from the previous exercise #6, and compare keff values from T16 and the output file
  - Add the following branch cases
    - Fuel temp=1500K, Boron=1300 ppm, control rods in
  - Can you calculate control rod worth at 1500K and 900K from T16 file? How about with and without boron?
  - Can we use FUEL instead of GAD?



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Advanced Topics



OPT, shield, basis, property cards

Fast execution options for testing

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shield

- shield : controls set of material regions with independently self-shielded cross-sections
- shield M_1=*XTYPE* M_2=*XTYPE* … M_i=*XTYPE* … M_N= *XTYPE*
- M_i – Material name (FUEL.1) or Material class (FUEL) or ALL for all materials
- XTYPE
  - N for no expansion of input materials for shielding (each input material has a single cross section set and is depleted with independent isotopics)
  - P for pin expansion (each input material **in each pin** has a single cross section set and is depleted with independent isotopics)
  - R for ring expansion (each input material **in each pin/ring** has a single cross section set and is depleted with independent isotopics)
- Default: shield ALL=N FUEL=R CNTL=R BP=R

OPT advanced options card

- Polaris uses an extensive set of options, provided for manipulating the solvers and output.
  - Most option cards support a key=value style of input, with reasonable defaults in place for all parameters
  - **KEFF**, ESSM, BOND, **DEPL**, CRITSPEC, PRINT, FG
    - option<*KEFF*> - eigenvalue (opt KEFF [key_1=val_1 key_2=val_2 … key_i=vali … key_N=val_N])

key	*value type*	*details*	*default*
NumAzim	*Int*	number of azimuthal angles per octant	20
NumPolar	*Int*	number of polar angles per octant	3
PnOrder	*Int*	scattering order	2
RaySpacing	*Real*	spacing between MoC rays	0.04 cm

    - Keff options provide control over fidelity of MOC transport solver.
    - RaySpacing is the most used option because of IFBA modeling.
    - The default ray spacing in Polaris is 0.04 cm (400 microns); this is too coarse for IFBA
    - To refine the ray spacing use, opt KEFF RaySpacing=0.01 (recommended)

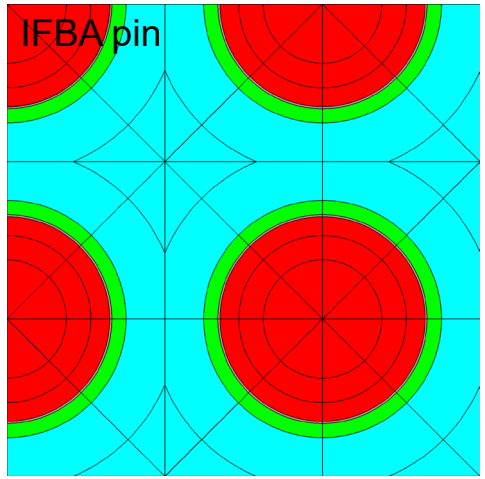
IFBA

```
=polaris
lib "broad_n"
system PWR
geom W17 : ASSM 3 1.26 SE
%--------------------------------------%
% comps and mats
%--------------------------------------%
comp c_f31 : UOX 3.1
mat FUEL.1 : c_f31 10.26
comp c_enrB : WT B10=50 B11=50
comp c_ifba : FORM Zr=1 c_enrB=2
mat BP.1 : c_ifba 3.85
%--------------------------------------%
% pins and mesh
%--------------------------------------%
pin B : 0.4096 0.4106 0.418 0.475
      : FUEL.1 BP     GAP   CLAD
pin F : 0.4096 0.418 0.475
      : FUEL.1 GAP   CLAD
mesh FUEL : nr=3
pinmap
 B
 F F
power 40
bu 0 .1 1 2 4 6 8 10
shield ALL=N FUEL=P BP=P
opt KEFF RaySpacing=0.01
state ALL  : temp=590
      COOL : dens=.68 boron=900
      CLAD : temp=700 FUEL : temp=900
end
```

- Integral Fuel Burnable Absorber
- spray-on coating of ZrB_2 with enriched B-10
- ~10 microns thick

Table 11: IFBA Fuel Rod Specification

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



option CRITSPEC

3.2.6.5 option<CRITSPEC> – critical spectrum

opt *CRITSPEC* [key_1=val_1 key_2=val_2 … key_i=val_i … key_N=val_N]

key	*value type*	*details*	*default*
Mode	*String*	critical spectrum mode "SEARCH": search for critical mode (k-eff=1) "SPECIFIED": provide B2 below "NONE": do not use critical spectrum	"SEARCH"
B2	*Real*	value of critical buckling if Mode="SPECIFIED" units: cm^{-2}	0.0
Method	*String*	critical spectrum system "B1": solve the B_1 equations "P1": solve the P_1 equations	"P1"

Examples

```
% enable critical buckling search using B1 equations for a buckling of 1e-3
opt CRITSPEC
  Mode="SPECIFIED"
  B2=1e-3
  Method="B1"
```

- options to control the critical spectrum calculation
- by default, the critical spectrum search is enabled
- to disable

opt CRITSPEC Mode='none'

- to specify a buckling value

opt CRITSPEC B2=0.001 Mode='specified'

- P1 is default, to set to B1

opt CRITSPEC Method='B1'

option PRINT

3.2.6.6 option<PRINT> – printing

opt *PRINT* [key_1=val_1 key_2=val_2 … key_i=val_i … key_N=val_N]

key	*value type*	*details*	*default*
XSSummary	*Bool*	print a cross section summary in the output file	true
CritSpecSummary	*String*	print critical spectrum summary "NONE": no print out "BUCKLING": limited buckling info "SPECTRUM": full spectrum	"BUCKLING"
XFile16	*Bool*	output a TRITON xfile016 nodal data library	false
InputDataContainer	*Bool*	print out the input data container	true

- printing options
- to print the txtfile16

opt PRINT XFile16=yes

- to print the critical spectrum

opt PRINT CritSpecSummary='spectrum'

option FG

3.2.6.7 option<FG> – few-group cross-section generation

opt *FG*
[AdjointMode=String InvVelMode=String]
[: b_1 b_2 … b_i … b_N]
[: E_1 E_2 … E_i … E_{N-1}]

param	*type*	*details*	*default*
AdjointMode	*String*	type of adjoint calculation to use in few-group data generation "INFMED": infinite medium adjoint "CRITICAL": critical spectrum adjoint "UNIFORM": uniform adjoint	"INFMED"
InvVelMode	*String*	weighting option for few-group inverse velocities "FORWARD": forward flux weighting "ADJOINT": adjoint flux weighting	"FORWARD"
b_i	*Real*	list of burnups to include in output few-group cross section database, e.g. XFile16 output units: GWd/MTHM	all burnups available
E_i	*Real*	note descending order and only N-1 divisions are needed for an N group structure E_0 is maximum energy (typically 2e7 eV) E_N is minimum (typically 1e-5 eV) units: eV	0.625 eV division (two groups)

- Few-group XS options
- Defaults are fine
- Example:

opt FG : 0 1 5 : 1000 1

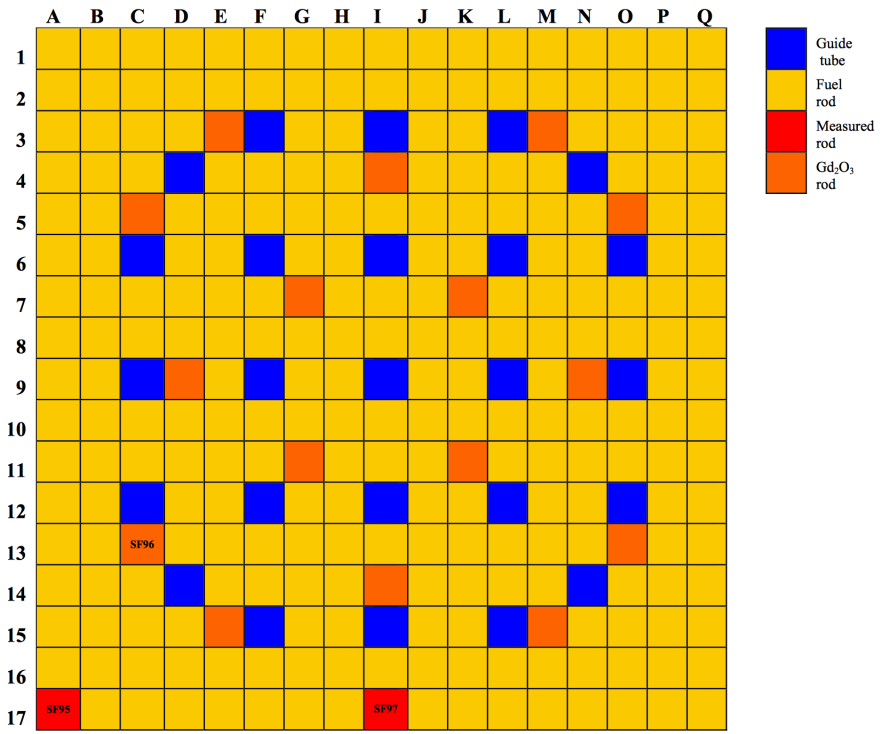
- "0 1 5" implies branch calculations are only performed at these burnups
- These must be a subset of the depletion burnups
- The txtfile16 will only have FG XS at "0 1 5" GWD/MTHM
- "1000 1" implies a 3 group XS structure
  1. 2e7 eV to 1000 eV
  2. 1000 eV to 1 eV
  3. 1 eV to 1e-5 eV

basis

```
mat FUEL.1 : uo2        temp=900
mat FUEL.2 : uo2_gd     temp=900
mat FUEL.3 : uo2        temp=900
mat CLAD.1 : fuel_clad temp=600
mat TUBE.1 : gt_clad    temp=600
mat COOL.1 : coolant    temp=576
%-------------------------------------%
% pins and mesh
%-------------------------------------%
pin F : 0.4025 0.475 : FUEL.1 CLAD
pin R : 0.4025 0.475 : FUEL.2 CLAD
pin B : 0.4025 0.475 : FUEL.3 CLAD
pin G : 0.573  0.613 : COOL.1 TUBE
mesh FUEL.1 : nr=3
mesh FUEL.2 : nr=5
mesh FUEL.3 : nr=3
%-------------------------------------%
% maps
%-------------------------------------%
pinmap
   G
   F F
   F F R
   G F F G
   F F F F F
   R F F F F G
   G F F G R F F
   F F F F F F F F
   B F F F F F F F F
%-------------------------------------%
% state
%-------------------------------------%
basis ALL=no FUEL.3=yes
shield ALL=N FUEL.1=P FUEL.2=R FUEL.3=P
pow 38.6 dt 1 25 25 50 50 50 50 50 84
pow 0    dt 88
pow 38.6 dt 1 50 50 100 100 101
pow 0 dt 62
pow 38.6 dt 1 50 50 100 100 105
end
```

basis M_1=yes|no M_2=yes|no … M_i=yes|no … M_N= yes|no

- M_i – Material name or Material class
  - yes – the power referenced on the power card includes this material's power (assumed deposited locally)
  - no – material is not part of the power basis



- Default: ALL=yes, meaning the power given on the power card is the power produced by all materials (power generated by fission and capture)
- If FUEL.3 is the basis material:
  basis ALL=no FUEL.3=yes
  the ALL=no disables all the materials before FUEL.3 is enabled

Fast execution (but not accurate) options

```
%--------------------------------------%
% fast options
%--------------------------------------%
lib "broad_n"
opt ESSM NumPolar=1 NumAzim=1 RaySpacing=0.08
opt KEFF NumPolar=1 NumAzim=1 RaySpacing=0.08
         PnOrder=0 TransportCorrection=no
         EigSolver='power'
         EigMaxIterations=1
         DownScatterSolver='source'
         DownScatterMaxIterations=1
         UpscatterSolver='gauss_seidel'
         UpscatterMaxIterations=1
         UpscatterInnerSolver='source'
         UpscatterInnerMaxIterations=1
opt DEPL TrackingSet='none'
         Method='predictor'
         NumSubSteps=1
opt CRITSPEC Mode='none'
shield ALL=N
opt GEOM MeshNumRings=1
         MeshNumSectors=1
         MeshNumX=1
         MeshNumY=1
%optional - comment out mesh cards
```

```
%--------------------------------------%
% fast options
%--------------------------------------%
lib "broad_n"
opt ESSM NumPolar=1 NumAzim=1 RaySpacing=0.08
opt KEFF NumPolar=1 NumAzim=1 RaySpacing=0.08
        PnOrder=0 TransportCorrection=no
        EigSolver='power'
        EigMaxIterations=1
        DownScatterSolver='source'
        DownScatterMaxIterations=1
        UpscatterSolver='gauss_seidel'
        UpscatterMaxIterations=1
        UpscatterInnerSolver='source'
        UpscatterInnerMaxIterations=1
opt DEPL NumSubSteps=1
opt CRITSPEC Mode='none'
```

property

- property<SOLP> - soluble poison by weight
  - prop PNAME M1 … : SOLP poison [scale=<*PPM*>|*PCT*|*ABS*]
- property<DOPANT> - fuel dopant by weight
  - prop PNAME M1 … : DOPANT dopant [scale=<PPM>|PCT|ABS]
- property<TWOPHASE> - density property used to control two phase mixtures
  - prop PNAME M1 : TWOPHASE liqden=Real vapden=Real

```
% define a TWOPHASE combination for moderator and coolant
prop vf MOD COOL : TWOPHASE 0.7 0.04
```

```
% define a soluble boron property for moderator
% and coolant material classes
% using natural boron
prop boron MOD COOL : SOLP B

% investigate coolant crud/impurity activation
%  1. define a general impurity property to mix in coolant,
  comp crud : NUM Ni=12.7 Cr=2.3 Fe=-100 %mostly Fe
  prop impurity COOL : SOLP crud
% 2. create coolant material with 100ppm of crud
  mat COOL.1 : LW dens=0.75 : impurity=100
% 3. make sure to "deplete" coolant so crud gets activated
  deplete COOL=true
```

```
% define three dopants properties for the fuel
% using predefined Cr2O3, Al2O3, and BeO
% then dope (deferred definition) fuel with 0.3% chromia,
% 0.2% alumina, 0.1% beryllia
prop Cr2O3 FUEL: DOPANT Cr2O3
prop Al2O3 FUEL: DOPANT Al2O3
prop BeO   FUEL: DOPANT BeO
mat FUEL.1 : uox_e310  temp=565 : Cr2O3=1000

% can also set the values through system properties
% works for both PWR and BWR
=polaris
title "pincell with UOX fuel doped with Cr2O3, Al2O3, and BeO"
lib "broad_lwr"
sys PWR
geom wec17 : ASSM 1 1.26
comp uox_e310 : UOX 3.10
mat FUEL.1 : uox_e310  10.5 : cr2o3=3000 al2o3=2000 beo=1000
pin 1 : 0.4096 0.418 0.475 : FUEL.1 GAP CLAD
```