SIMULATING THE SPENT FUEL RECIPE OF A SODIUM-COOLED FAST REACTOR

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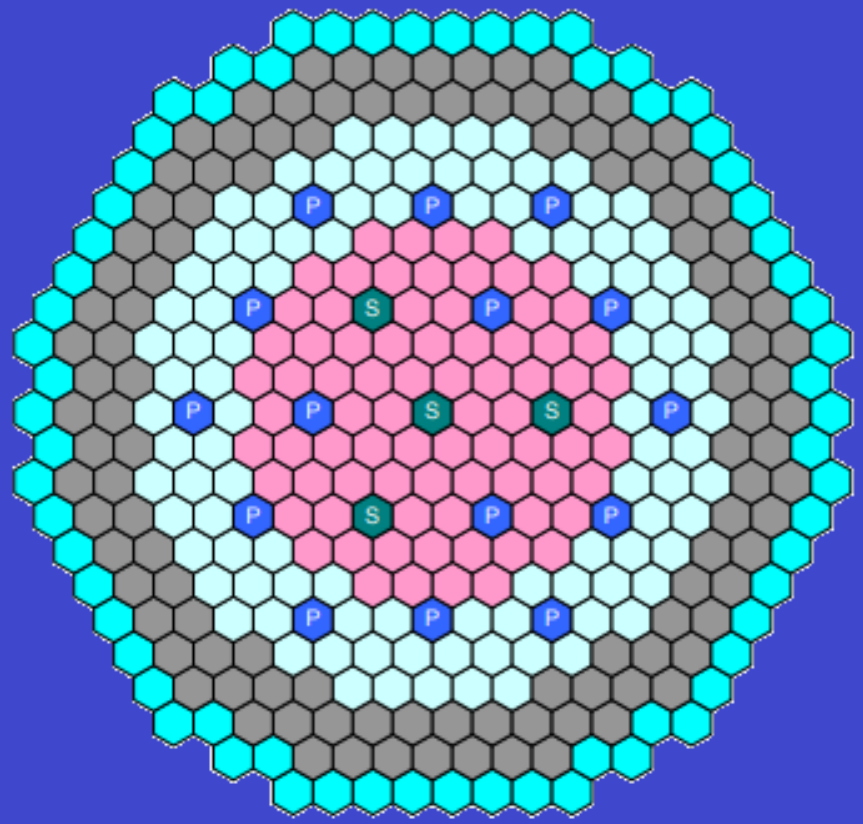
MOTIVATION

- Climate Change
- Peak Oil
- Gen-IV Reactor
  - Transition Scenarios
- Cyclus
  - RAVEN and Reduced-Order Models

REACTOR BENCHMARK

- OECD Benchmark
- Octagonal Geometry
- 379 Hexagonal Subassemblies
- 5 Layers of Fuel
- No Blanket
- 1-GWth
- Circular Pins
- Pin Pitch = $^{P}/_{n} \tan(^{\pi}/_{6}) = {}^{9.38021}/_{n}$



	Unit	Value
Reactor power	MW-thermal	1000.0
Coolant temperature	°C	432.5
Average core structural temperature	°C	432.5
Average fuel temperature	°C	534.0

FRESH FUEL COMPOSITION

- Metal Fuel Form
- 24 isotopes including Uranium, Neptunium, Plutonium, Americium, Californium, Zirconium, and Molybdenum
- 5 Vertical “Layers” of Fuel
- Inner and Outer Core
- Same Isotopes at Different Abundances in Inner/Outer Core and Different Layers

INNER CORE FUEL COMPOSITION

Nuclide	Upper boundary from active core bottom (cm)				
	17.16	34.33	51.49	68.66	85.82
^{234}U	1.1369E-06	1.0856E-06	1.0727E-06	1.1028E-06	1.1759E-06
^{235}U	3.0421E-05	2.9338E-05	2.8961E-05	3.0070E-05	3.2571E-05
^{236}U	2.4896E-06	2.5117E-06	2.5536E-06	2.3779E-06	2.0226E-06
^{238}U	1.9613E-02	1.9474E-02	1.9433E-02	1.9550E-02	1.9801E-02
^{237}Np	4.6686E-05	4.6962E-05	4.6782E-05	4.7603E-05	4.8895E-05
^{236}Pu	4.9700E-10	5.5883E-10	5.6701E-10	5.5075E-10	4.8775E-10
^{238}Pu	1.1695E-04	1.1284E-04	1.1196E-04	1.1370E-04	1.1829E-04
^{239}Pu	2.2076E-03	2.1814E-03	2.1754E-03	2.1813E-03	2.2011E-03
^{240}Pu	1.3244E-03	1.2955E-03	1.2902E-03	1.2986E-03	1.3248E-03
^{241}Pu	1.9375E-04	1.8610E-04	1.8518E-04	1.8537E-04	1.8845E-04
^{242}Pu	2.9277E-04	2.8911E-04	2.8818E-04	2.9038E-04	2.9569E-04
^{241}Am	1.0791E-04	1.0465E-04	1.0353E-04	1.0686E-04	1.1421E-04
^{242m}Am	9.2989E-06	9.0848E-06	9.0224E-06	9.1756E-06	9.4890E-06
^{243}Am	1.0017E-04	9.8324E-05	9.7993E-05	9.8630E-05	1.0032E-04
^{242}Cm	5.6250E-06	5.8208E-06	5.9476E-06	5.4901E-06	4.5416E-06
^{243}Cm	5.4321E-07	5.0246E-07	5.0136E-07	4.8876E-07	4.8480E-07
^{244}Cm	6.7240E-05	6.5722E-05	6.5622E-05	6.5349E-05	6.5394E-05
^{245}Cm	1.7397E-05	1.6743E-05	1.6663E-05	1.6696E-05	1.7026E-05
^{246}Cm	9.2285E-06	9.1426E-06	9.1307E-06	9.1364E-06	9.1805E-06
Zr	7.2802E-03	7.2802E-03	7.2802E-03	7.2802E-03	7.2802E-03
[a] Mo	9.2873E-04	1.1464E-03	1.2031E-03	1.0625E-03	7.4065E-04

a) representative for pseudo fission product

▸OUTER CORE FUEL COMPOSITION

Nuclide	Upper boundary from active core bottom (cm)				
	17.16	34.33	51.49	68.66	85.82
^{234}U	1.6317E-06	1.5766E-06	1.5638E-06	1.5894E-06	1.6552E-06
^{235}U	3.0822E-05	2.9870E-05	2.9561E-05	3.0391E-05	3.2250E-05
^{236}U	1.7881E-06	1.8534E-06	1.8941E-06	1.7528E-06	1.4710E-06
^{238}U	1.8244E-02	1.8144E-02	1.8115E-02	1.8191E-02	1.8359E-02
^{237}Np	9.8244E-05	9.7300E-05	9.6775E-05	9.8481E-05	1.0175E-04
^{236}Pu	7.1175E-10	8.2505E-10	8.4282E-10	8.0703E-10	6.8053E-10
^{238}Pu	1.6436E-04	1.6026E-04	1.5949E-04	1.6063E-04	1.6416E-04
^{239}Pu	2.8147E-03	2.7664E-03	2.7538E-03	2.7786E-03	2.8416E-03
^{240}Pu	1.7467E-03	1.7191E-03	1.7135E-03	1.7231E-03	1.7508E-03
^{241}Pu	2.8976E-04	2.8138E-04	2.8012E-04	2.8135E-04	2.8697E-04
^{242}Pu	4.0754E-04	4.0412E-04	4.0321E-04	4.0530E-04	4.1028E-04
^{241}Am	1.8607E-04	1.8127E-04	1.7970E-04	1.8397E-04	1.9339E-04
^{242m}Am	1.2185E-05	1.2045E-05	1.2021E-05	1.2039E-05	1.2064E-05
^{243}Am	1.3234E-04	1.3019E-04	1.2985E-04	1.3036E-04	1.3206E-04
^{242}Cm	6.4688E-06	6.8630E-06	7.0553E-06	6.4446E-06	5.1976E-06
^{243}Cm	6.3471E-07	6.0893E-07	6.0901E-07	5.9753E-07	5.9372E-07
^{244}Cm	8.0107E-05	7.8889E-05	7.8847E-05	7.8479E-05	7.8359E-05
^{245}Cm	2.0200E-05	1.9678E-05	1.9613E-05	1.9635E-05	1.9913E-05
^{246}Cm	1.0443E-05	1.0371E-05	1.0361E-05	1.0367E-05	1.0410E-05
Zr	7.2802E-03	7.2802E-03	7.2802E-03	7.2802E-03	7.2802E-03
$^{a)}Mo$	8.1524E-04	1.0174E-03	1.0697E-03	9.4870E-04	6.6172E-04

a) representative for pseudo fission product

SERPENT2

- Monte-Carlo based Simulation Software
- Universe-Based Constructive Solid Geometry
  - Pin < Subassembly < Lattice
- Continuous-Energy
- Developed at VTT Technical Research Centre of Finland
- Plain text Input File
  - Geometry
  - Material
  - Simulation Parameters
- Plain text and Image Output

MATERIAL CARDS

- Provide Alias and ZAID for Each Material In Reactor
- Provide Number Densities of Isotopes
- ACE, NFY, DEC Libraries for Material Properties
  - Courtesy of ARFC

```
% --- Fuel in inner core bottom (composition in atom density) (atoms/barn-cm):
mat in-fuel-bot sum burn 1
92234.09c   1.1369E-06  %U-234
92235.09c   3.0421E-05  %U-235
92236.09c   2.4896E-06  %U-236
92238.09c   1.9613E-02  %U-238
93237.09c   4.6686E-05  %Np-237
94236.09c   4.9700E-10  %Pu-236
94239.09c   1.1695E-04  %Pu-238
94239.09c   2.2076E-03  %Pu-239
94240.09c   1.3244E-03  %Pu-240
94241.09c   1.9375E-04  %Pu-241
94242.09c   2.9277E-04  %Pu-242
95241.09c   1.0791E-04  %Am-241
95342.09c   9.2989E-06  %Am-242m
95243.09c   1.0017E-04  %Am-243
96242.09c   5.6250E-06  %Cm-242
96243.09c   5.4321E-07  %Cm-243
96244.09c   6.7240E-05  %Cm-244
96245.09c   1.7397E-05  %Cm-245
96246.09c   9.2285E-06  %Cm-246
40000.09c   7.2802E-03  %Natural Zr
42000.09c   9.2873E-04  %a-Mo fission pseudo product
```

PIN CARDS

- A Universe of Coaxial Cylinders of Homogeneous Material
- Provide Alias of Fill Material and Outer Radius
- Outermost Region is Coolant

```
pin 10 %coolant
cool

pin 11 %inner core bottom
in-fuel-bot 0.3236
clad 0.3857
cool


pin 12 %outer core bottom
out-fuel-bot 0.3236
clad 0.3857
cool

pin 13 %reflector
refl  0.7557
cool

pin 14 %shielding
absonat 1.4277
clad    1.6794
cool

pin 15 %control
abso 2.2890
clad 2.3606
cool
```

GEOMETRY CODE

- Pictures of Benchmark Schematic next to Code to Model that Region of the Reactor

Driver Subassembly

```
lat 17 3 0 0 21 21 0.938021 %fuel pin pitch = 1.042245536cm
10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 11 11 11 11 11 11 11 11 11 11 10
  10 10 10 10 10 10 10 10 10 11 11 11 11 11 11 11 11 11 11 11 10
   10 10 10 10 10 10 10 10 11 11 11 11 11 11 11 11 11 11 11 11 10
    10 10 10 10 10 10 10 11 11 11 11 11 11 11 11 11 11 11 11 11 10
     10 10 10 10 10 10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10
      10 10 10 10 10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10
       10 10 10 10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10
        10 10 10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10
         10 10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10
          10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10
           10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10 10
            10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10 10 10
             10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10 10 10 10
              10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10 10 10 10 10
               10 11 11 11 11 11 11 11 11 11 11 11 11 11 11 10 10 10 10 10 10
                10 11 11 11 11 11 11 11 11 11 11 11 11 11 10 10 10 10 10 10 10
                 10 11 11 11 11 11 11 11 11 11 11 11 11 10 10 10 10 10 10 10 10
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                   10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
```
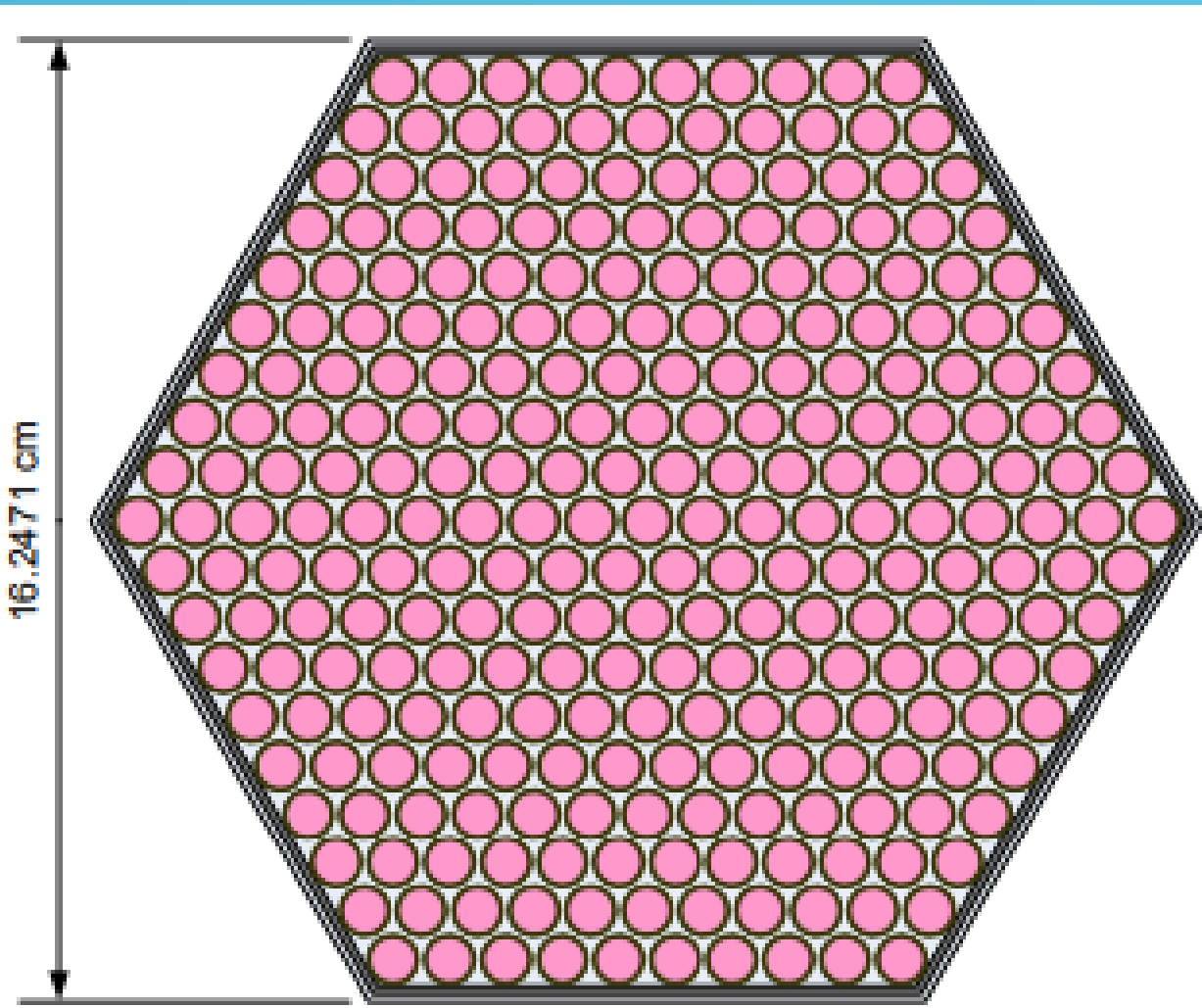
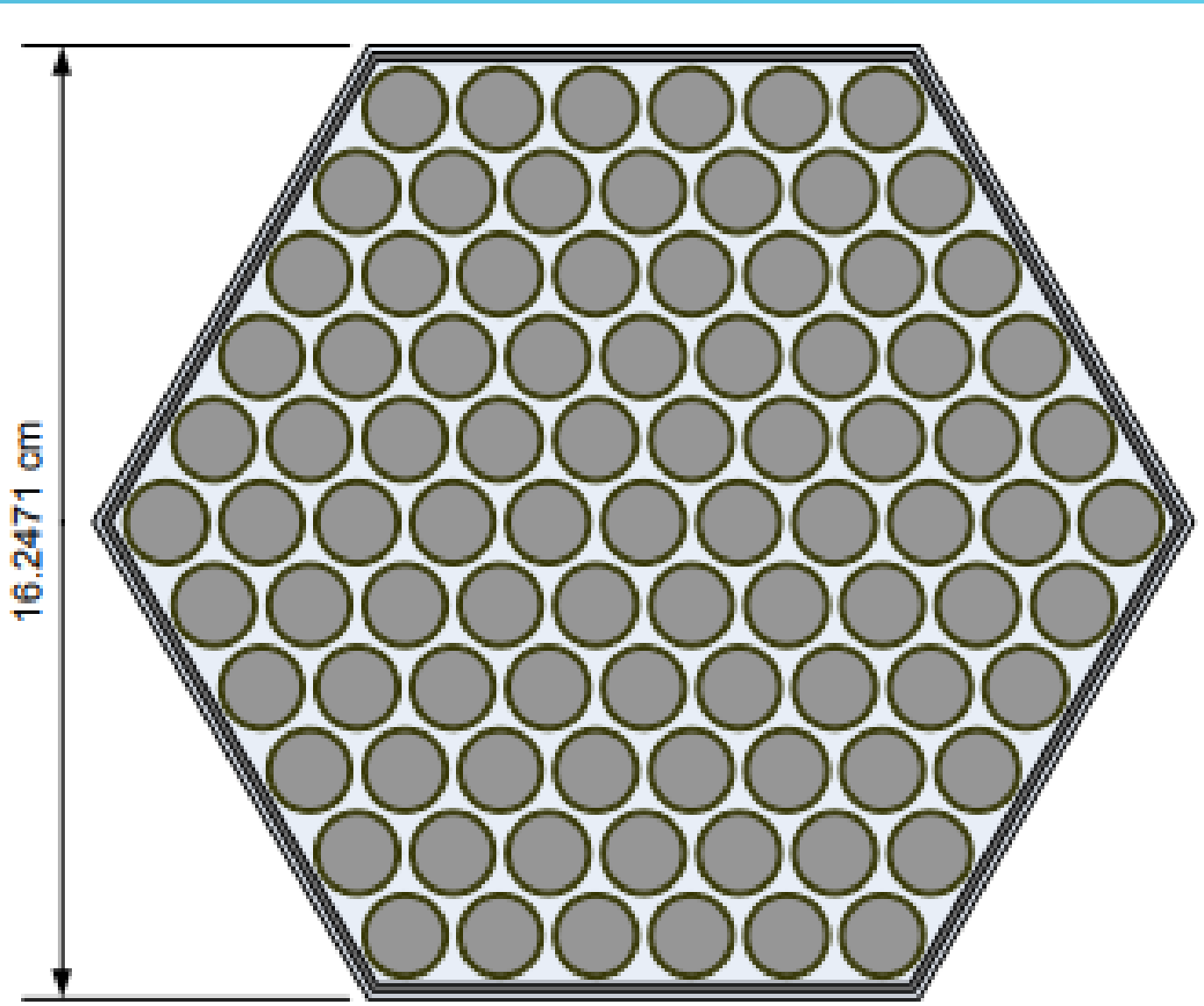



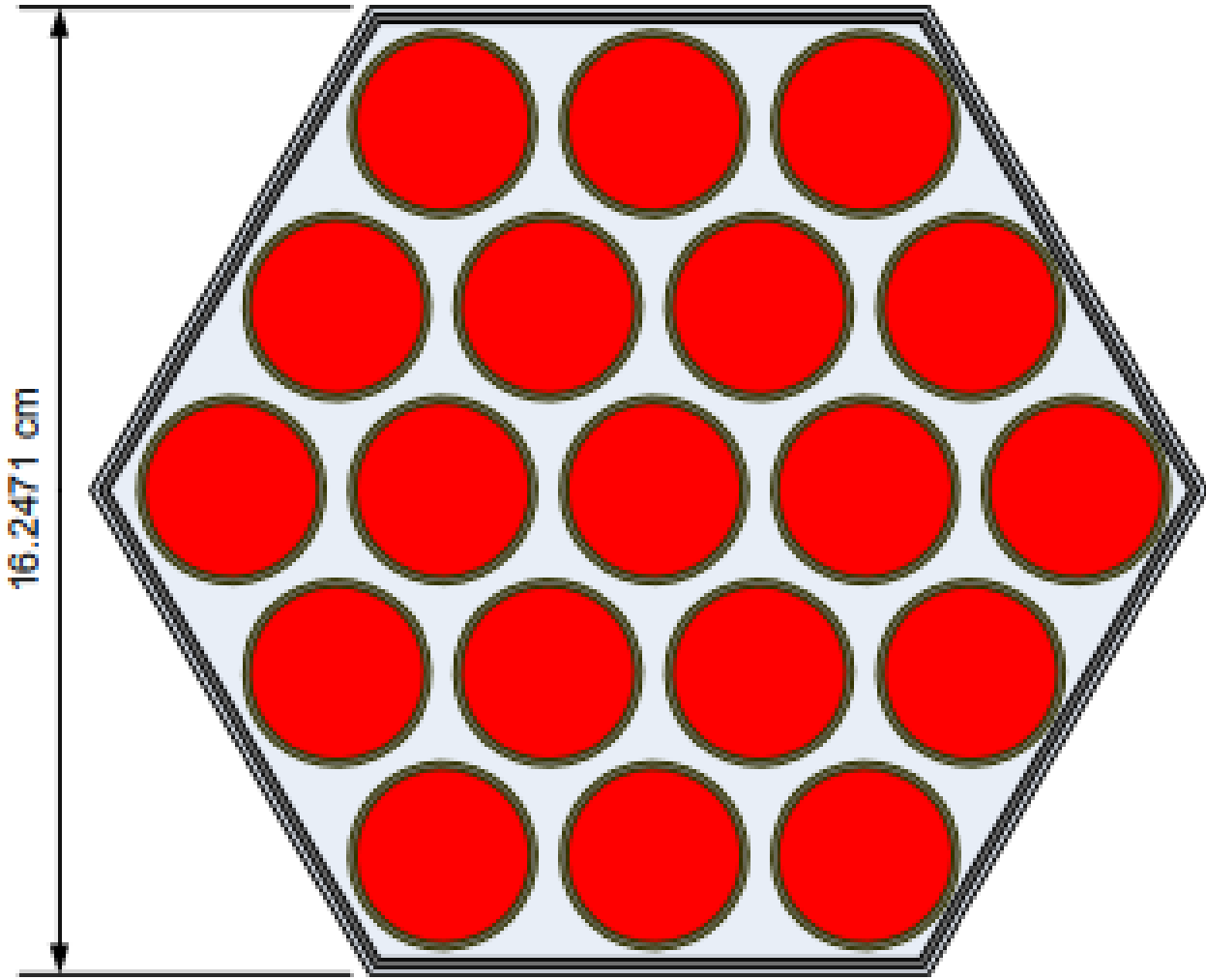
REFLECTOR SUBASSEMBLY

```
lat 23 3 0 0 13 13 1.56337 %reflector subassembly pin pitch = 1.9 cm
10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 13 13 13 13 13 13 10
  10 10 10 10 10 13 13 13 13 13 13 13 10
   10 10 10 10 13 13 13 13 13 13 13 13 10
    10 10 10 13 13 13 13 13 13 13 13 13 10
     10 10 13 13 13 13 13 13 13 13 13 13 10
      10 13 13 13 13 13 13 13 13 13 13 13 10
       10 13 13 13 13 13 13 13 13 13 13 10 10
        10 13 13 13 13 13 13 13 13 13 10 10 10
         10 13 13 13 13 13 13 13 13 10 10 10 10
          10 13 13 13 13 13 13 13 10 10 10 10 10
           10 13 13 13 13 13 13 10 10 10 10 10 10
            10 10 10 10 10 10 10 10 10 10 10 10 10
```



SHIELD SUBASSEMBLY

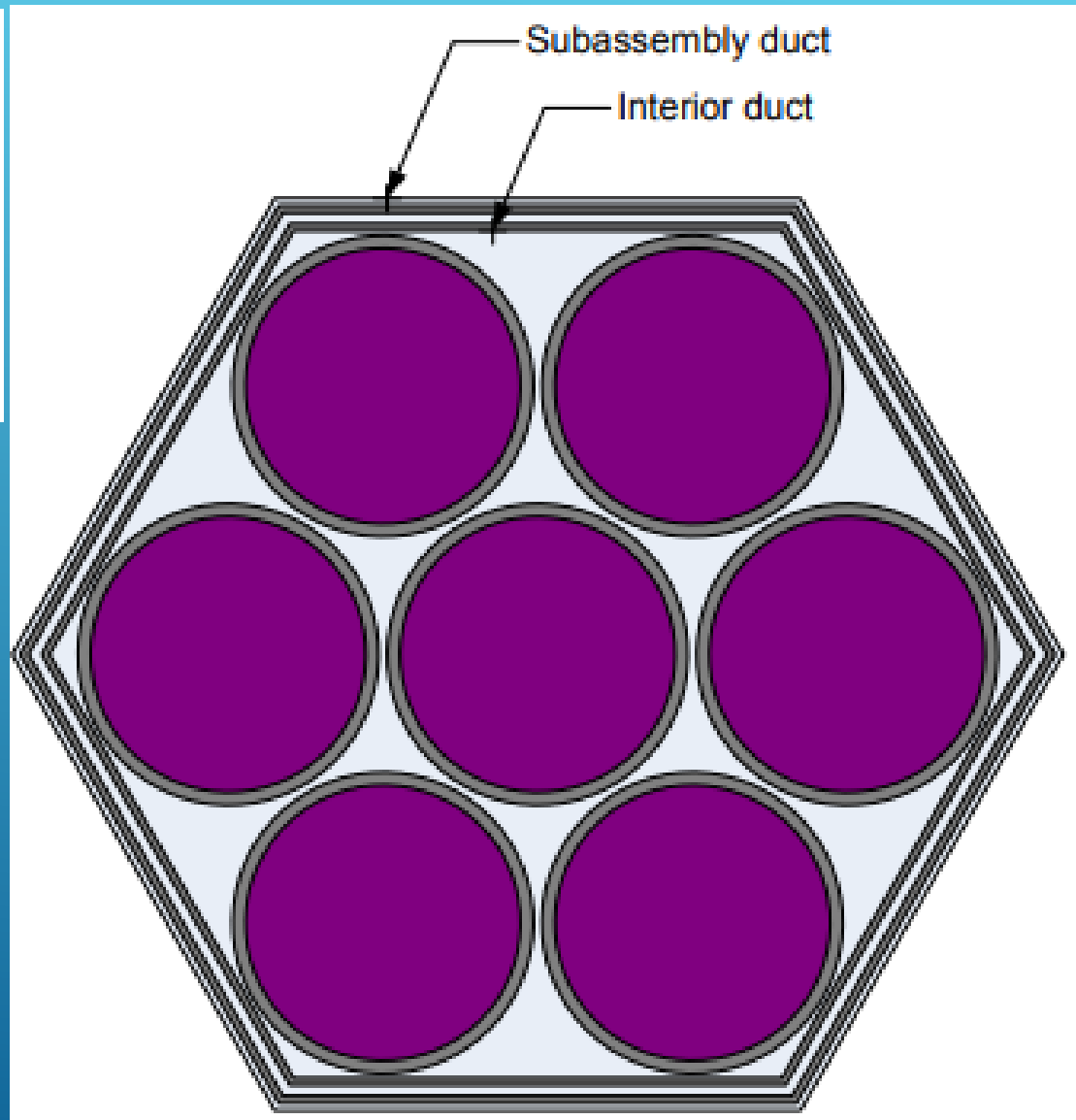
```
lat 24 3 0 0 7 7 3.12674 % pin pitch = 4.7cm
10 10 10 10 10 10 10
 10 10 10 14 14 14 10
  10 10 14 14 14 14 10
   10 14 14 14 14 14 10
    10 14 14 14 14 10 10
     10 14 14 14 10 10 10
      10 10 10 10 10 10 10
```



Section A-A

CONTROL ROD SUBASSEMBLY

```
lat 25 3 0 0 5 5 4.690105 %pin pitch = 1.9cm
10 10 10 10 10
 10 10 15 15 10
  10 15 15 15 10
   10 15 15 10 10
    10 10 10 10 10
```



LATTICE CARDS

- Position Subassemblies

With Universe Numbers

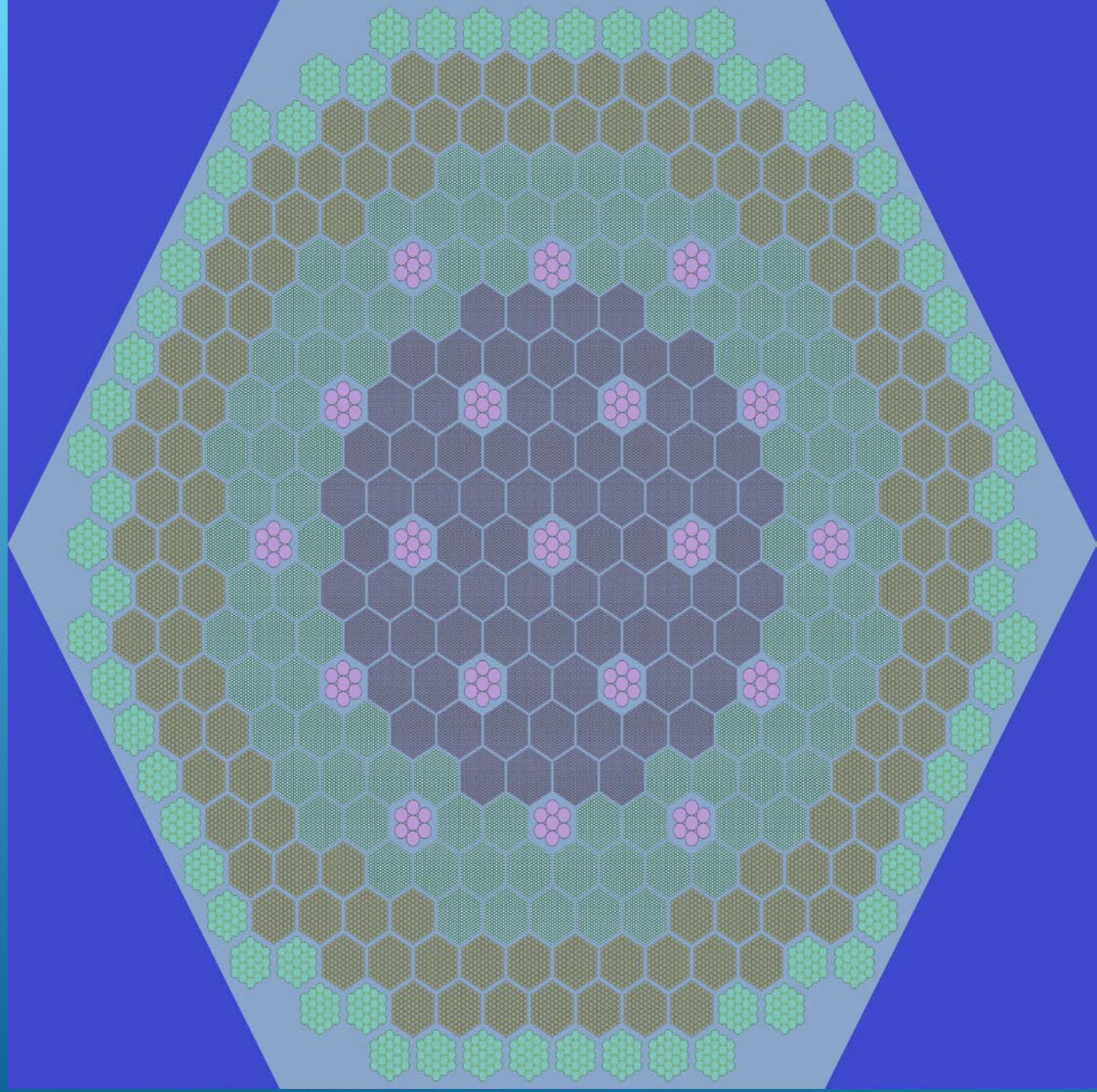
```
lat 1 2 0 0 25 25 16.2471 %bottom lattice
10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
 10 10 10 10 10 10 10 10 10 10 10 10 10 24 24 24 24 24 24 24 24 10 10 10
  10 10 10 10 10 10 10 10 10 10 10 10 24 24 23 23 23 23 23 23 23 24 24 10 10
   10 10 10 10 10 10 10 10 10 10 24 24 23 23 23 23 23 23 23 23 23 23 24 24 10
    10 10 10 10 10 10 10 10 10 24 23 23 23 23 18 18 18 18 18 23 23 23 23 24 10
     10 10 10 10 10 10 10 10 24 23 23 23 18 18 18 18 18 18 18 18 23 23 23 24 10
      10 10 10 10 10 10 10 10 24 23 23 18 18 25 18 18 25 18 18 25 18 18 23 23 24 10
       10 10 10 10 10 10 10 24 23 23 18 18 18 18 17 17 17 17 18 18 18 18 23 23 24 10
        10 10 10 10 10 10 24 23 23 18 18 18 17 17 17 17 17 17 17 18 18 18 23 23 24 10
         10 10 10 10 10 24 23 23 18 18 25 17 17 25 17 17 25 17 17 25 18 18 23 23 24 10
          10 10 10 10 24 23 23 18 18 18 17 17 17 17 17 17 17 17 17 17 18 18 18 23 23 24 10
           10 10 10 24 23 23 18 18 18 17 17 17 17 17 17 17 17 17 17 17 18 18 23 23 24 10 10
            10 10 24 23 23 18 25 18 17 25 17 17 25 17 17 25 17 18 25 18 23 23 24 10 10
             10 10 24 23 23 18 18 17 17 17 17 17 17 17 17 17 17 17 18 18 23 23 24 10 10 10
              10 24 23 23 18 18 18 17 17 17 17 17 17 17 17 17 17 17 18 18 18 23 23 24 10 10 10
               10 24 23 23 18 18 25 17 17 25 17 17 25 17 17 25 18 18 23 23 24 10 10 10 10
                10 24 23 23 18 18 18 17 17 17 17 17 17 17 18 18 18 23 23 24 10 10 10 10 10
                 10 24 23 23 18 18 18 18 17 17 17 17 18 18 18 18 23 23 24 10 10 10 10 10 10
                  10 24 23 23 18 18 25 18 18 25 18 18 25 18 18 23 23 24 10 10 10 10 10 10 10
                   10 24 23 23 23 18 18 18 18 18 18 18 18 23 23 23 24 10 10 10 10 10 10 10 10
                    10 24 23 23 23 23 18 18 18 18 18 23 23 23 23 24 10 10 10 10 10 10 10 10 10
                     10 24 24 23 23 23 23 23 23 23 23 23 24 24 10 10 10 10 10 10 10 10 10 10 10
                      10 10 24 24 23 23 23 23 23 23 23 24 24 10 10 10 10 10 10 10 10 10 10 10 10
                       10 10 10 24 24 24 24 24 24 24 24 10 10 10 10 10 10 10 10 10 10 10 10 10 10
                        10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
```

RESULTS

- Geometry Plots
  - Vertical and Horizontal Cross-Sections
- Burnup Plots
  - Before and After
- Depleted Fuel Content

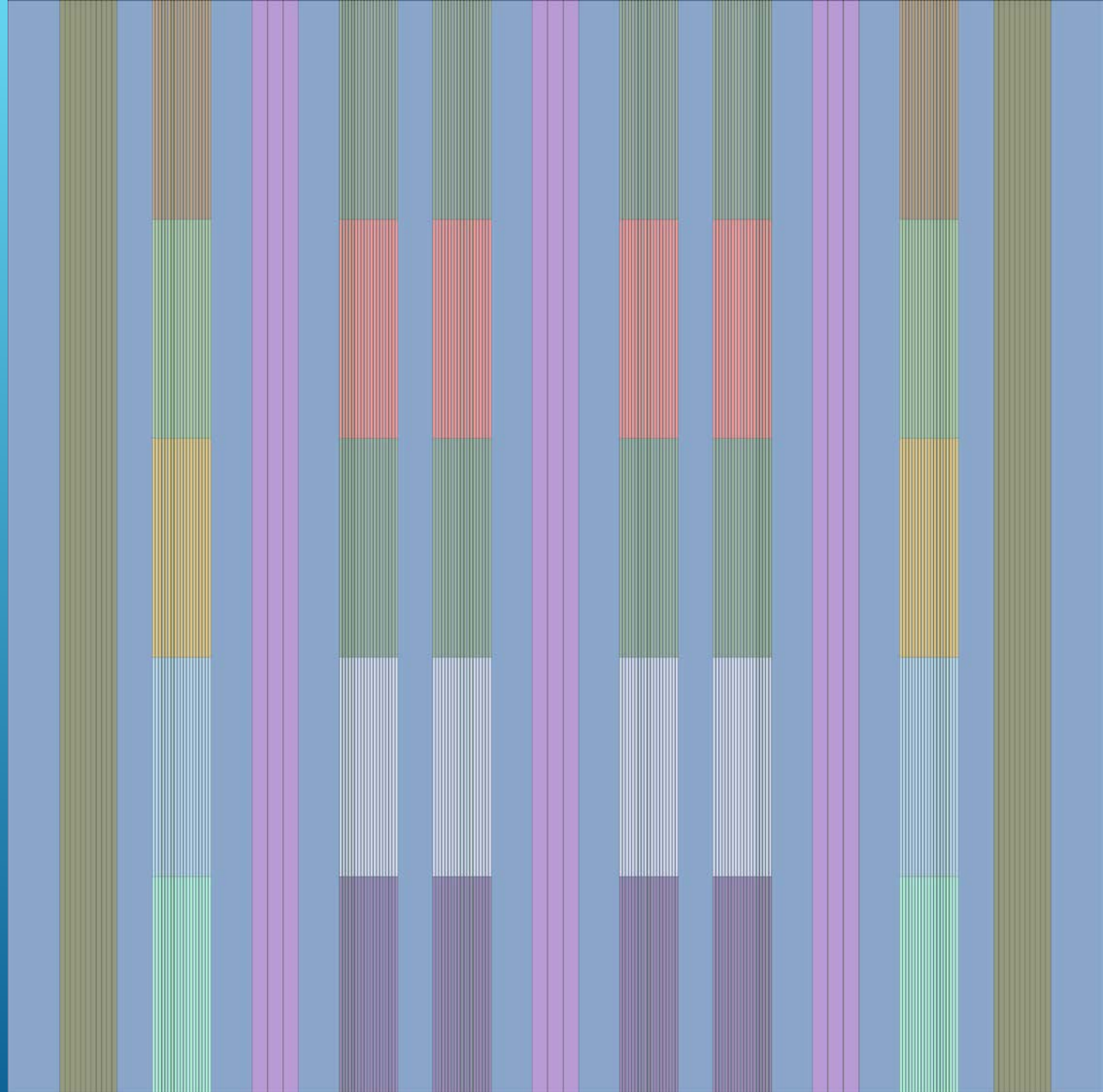
GEOMETRY PLOT

- View along Z-Axis
- Different Color Corresponds to Different Pin Universe



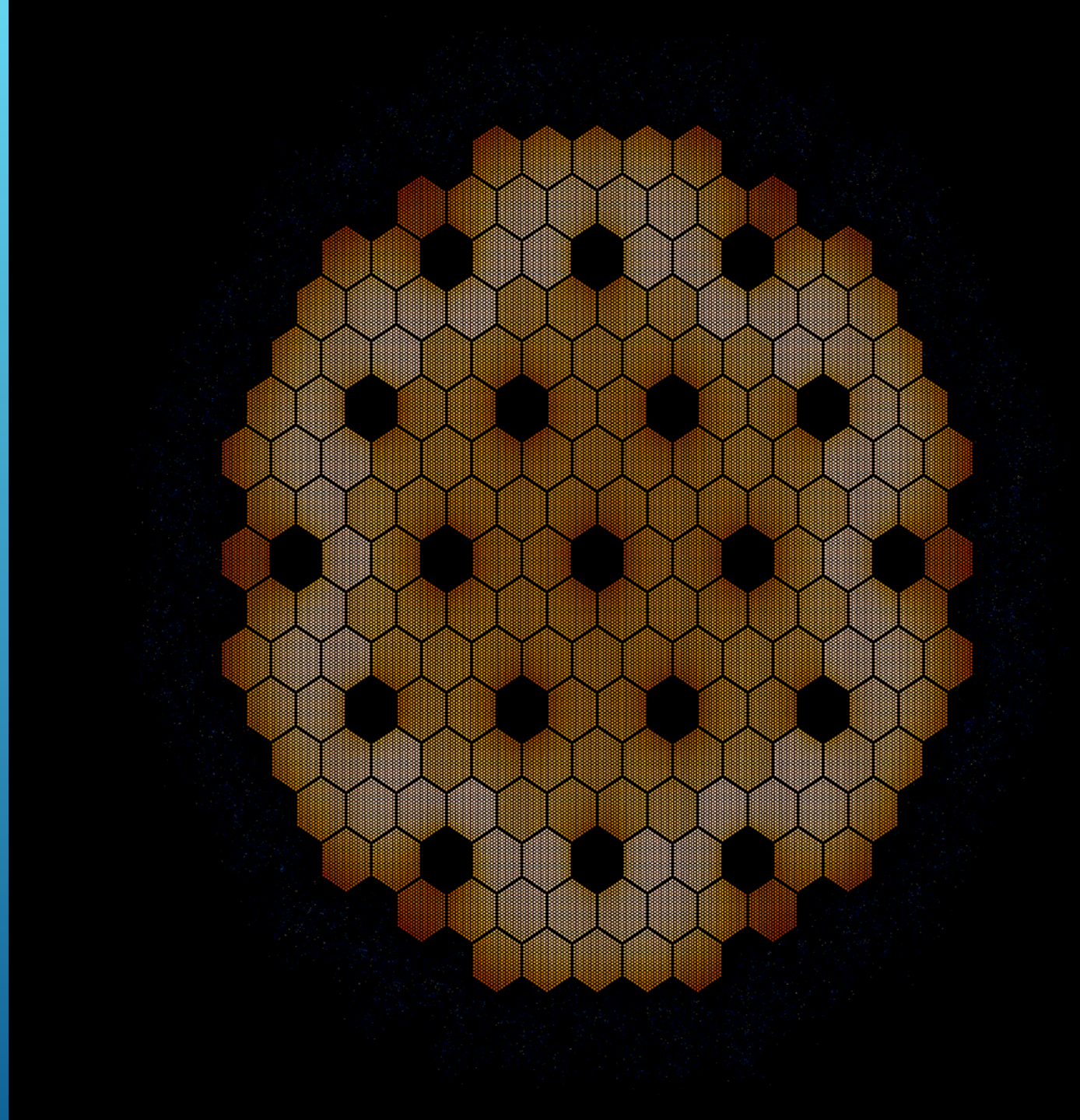
GEOMETRY PLOT

- View from Y-axis
- Five Layers of Fuel



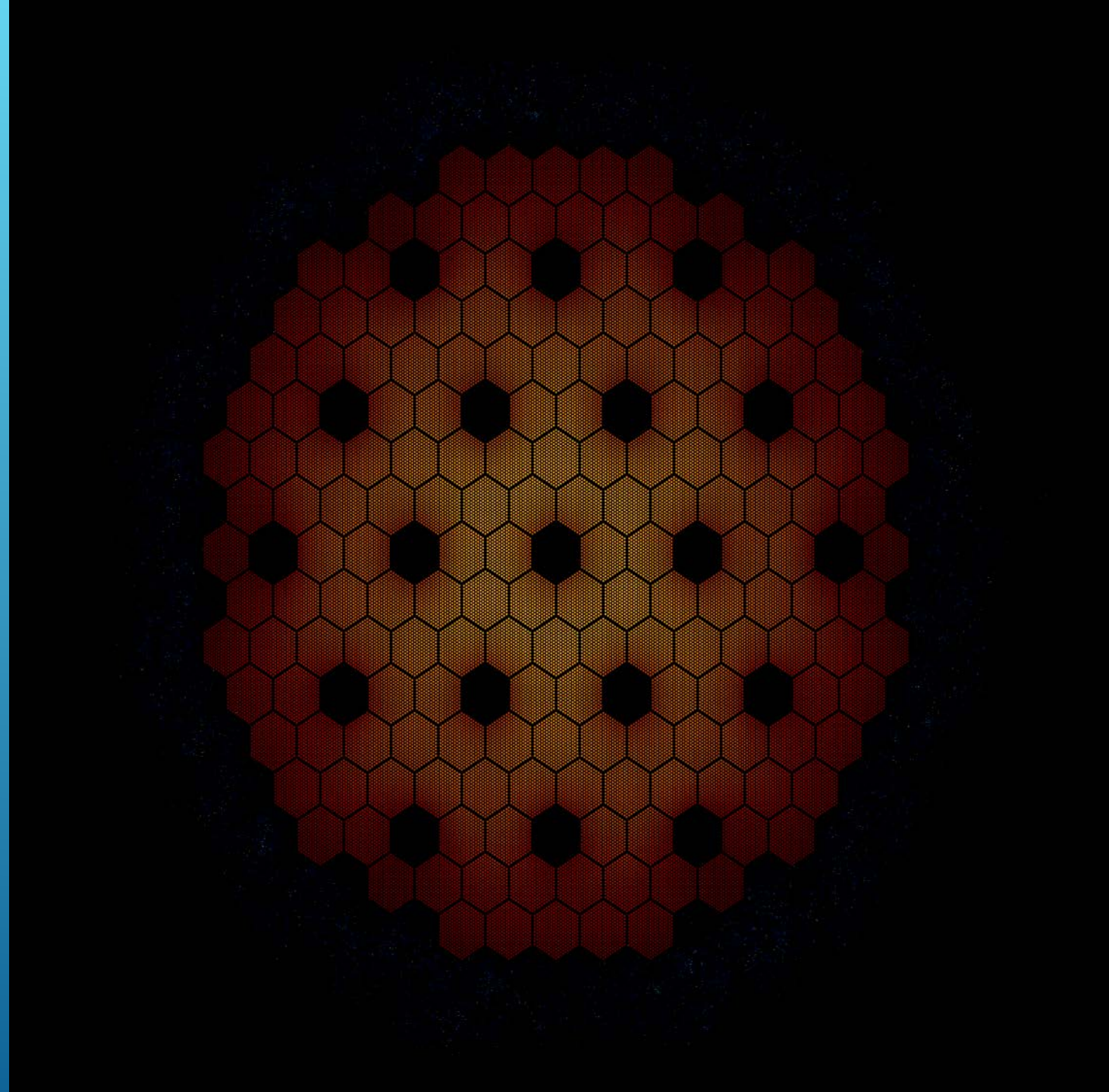
BURNUP PLOT - BEFORE

- Color Indicates Flux
- Absorbers Doing A Good Job



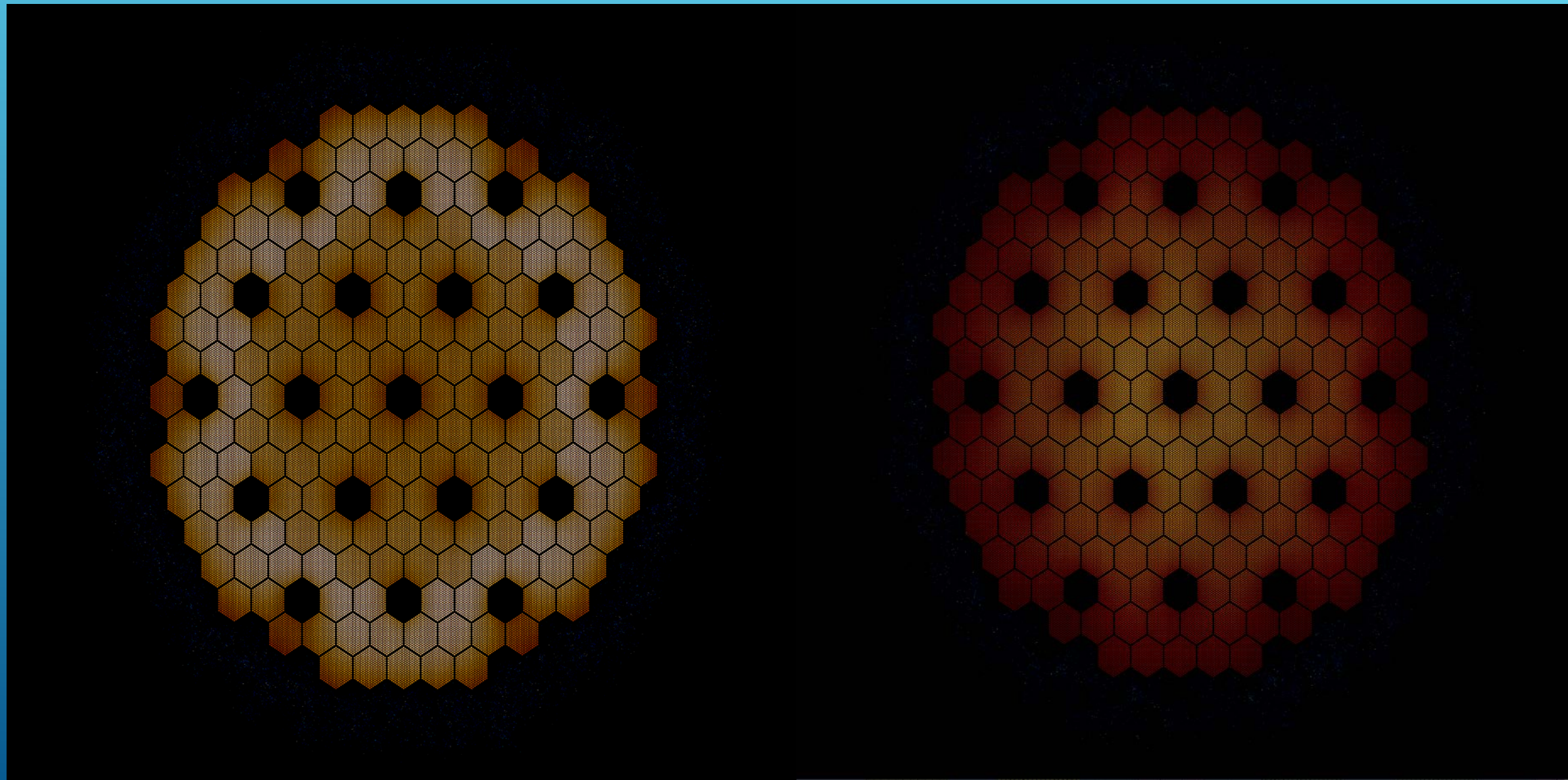
BURNUP PLOT - AFTER

- One Year Of Operation
- Dimmer Plot Indicates Refueling Is Needed



BEFORE

AFTER



USED FUEL COMPOSITION

- Over 2000 different nuclides
- “Recipe” Input for Cyclus
- Reduced Order Model for Raven

REFERENCES & ACKNOWLEDGEMENTS

- 1) OECD-NEA (February 2016). Benchmark for Neutronic Analysis of Sodium-cooled Fast Reactor Cores with Various Fuel Types and Core Sizes, Retrieved From: www.oecd-nea.org
- 2) J. Leppänen (June 18, 2015), Serpent – a Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code. VTT Technical Research Centre of Finland. Retrieved From: montecarlo.vtt.fi

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