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Verification of the 3-Region Advanced Test Reactor MCNP Model

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Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

Idaho National Laboratory

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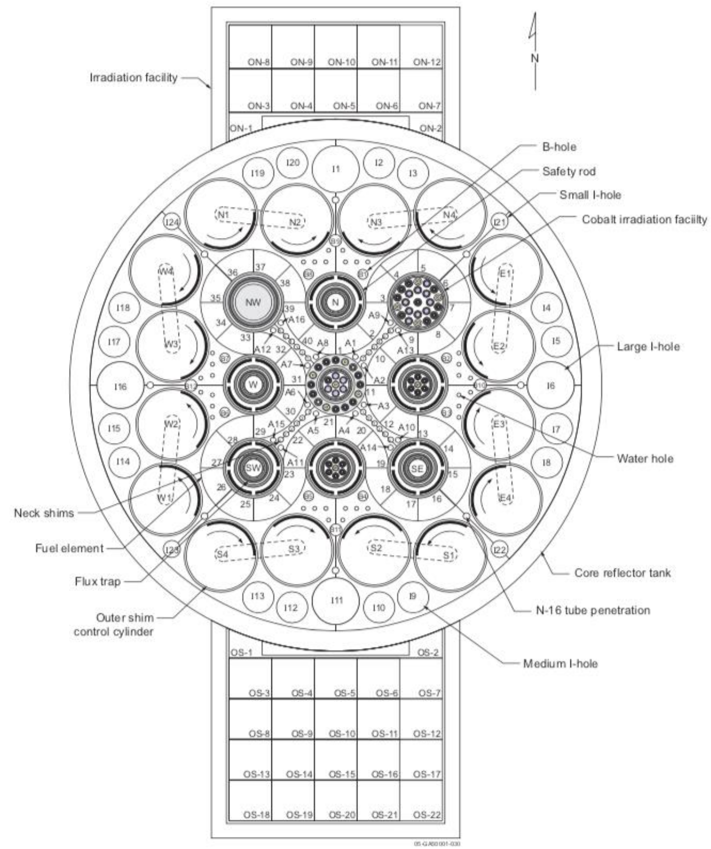
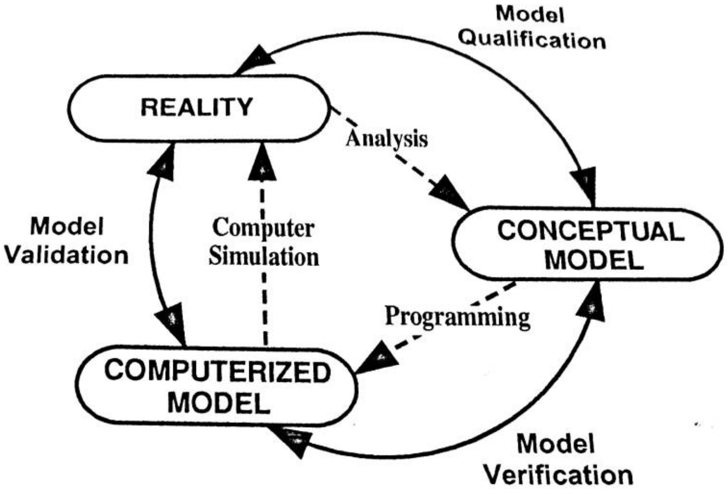
Background: Advanced Test Reactor



Background: Verification and Validation (V&V)

- Society for Computer Simulation (SCS)
  - Verification: ” the substantiation that a computerized model represents a conceptual model within specified limits of accuracy,”
  - Validation: ”substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model”



Background: Verification and Validation (V&V)

- US Department of Defense (DoD)
  - Verification: "the process of determining that a model implantation accurately represents the developer's conceptual description of the model”
  - Validation: "the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model”

Background: MCNP

- General-purpose, continuous-energy, generalized-geometry, time-dependent, Monte Carlo radiation transport code designed to track many particle types over broad ranges of energies
- MCNP has 7 standard tallies available for users.

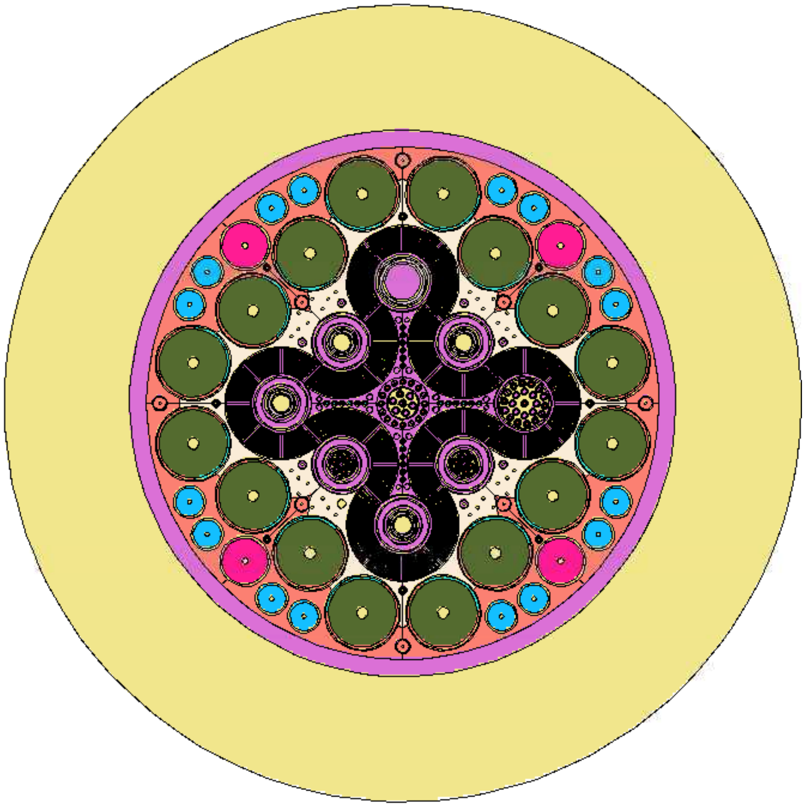
$$\bar{\phi}_V = \frac{1}{V}\int dE \int dt \int dV \int d\Omega\, \Psi(\vec{r}, \Omega, E, t)$$

$$H_t = \frac{\rho_a}{m}\int dE \int dt \int dV \int d\Omega\, \sigma_t(E) H(E) \Psi(\vec{r}, \hat{\Omega}, E, t)$$

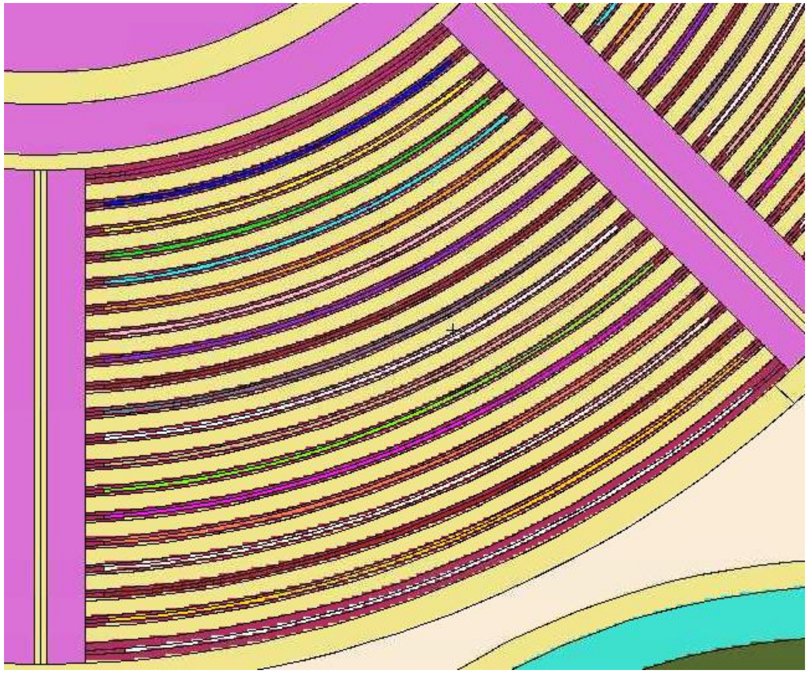
$$H_f = \frac{\rho_a}{m} Q \int dE \int dt \int dV \int d\Omega\, \sigma_f(E) \Psi(\vec{r}, \hat{\Omega}, E, t)$$

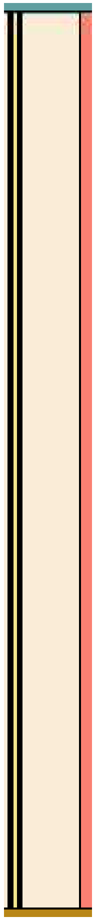
Background: 94-CIC

- "ADVANCED TEST REACTOR: SERPENTINE ARRANGEMENT OF HIGHLY ENRICHED WATER-MODERATED URANIUM-ALUMINIDE FUEL PLATES REFLECTED BY BERYLLIUM”
- https://www.oecd-nea.org/jcms/pl_24498/international-criticality-safety-benchmark-evaluation-project-icsbep.

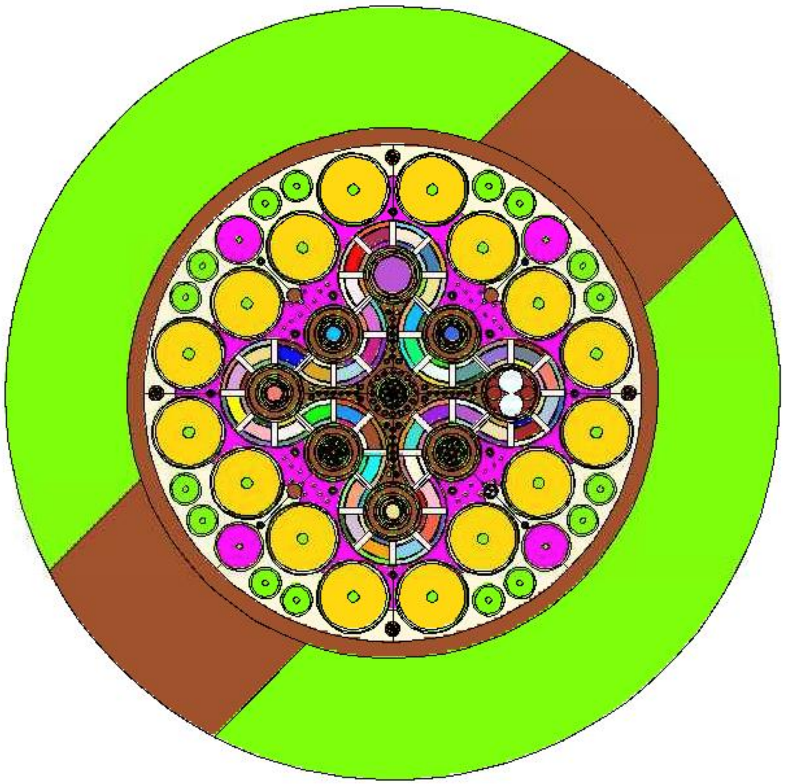


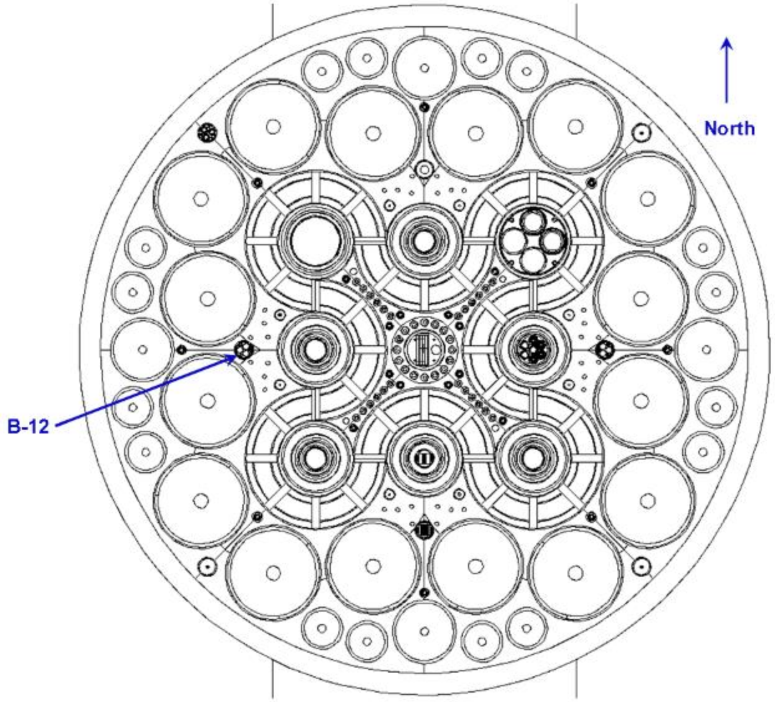
Background: 19-Plate Model



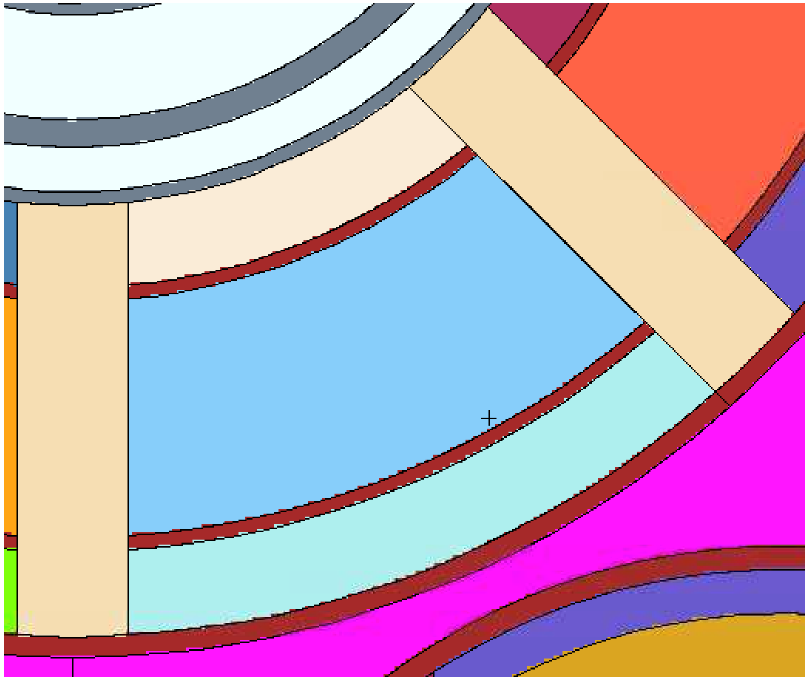


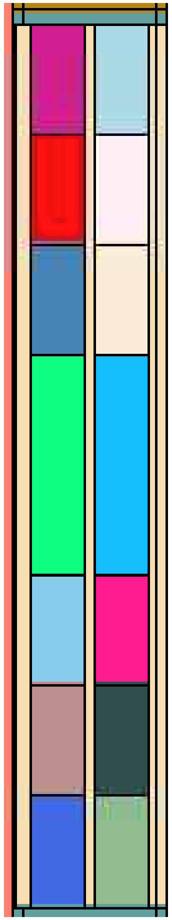
Background: 3-Region Model





Background: 3-Region Model



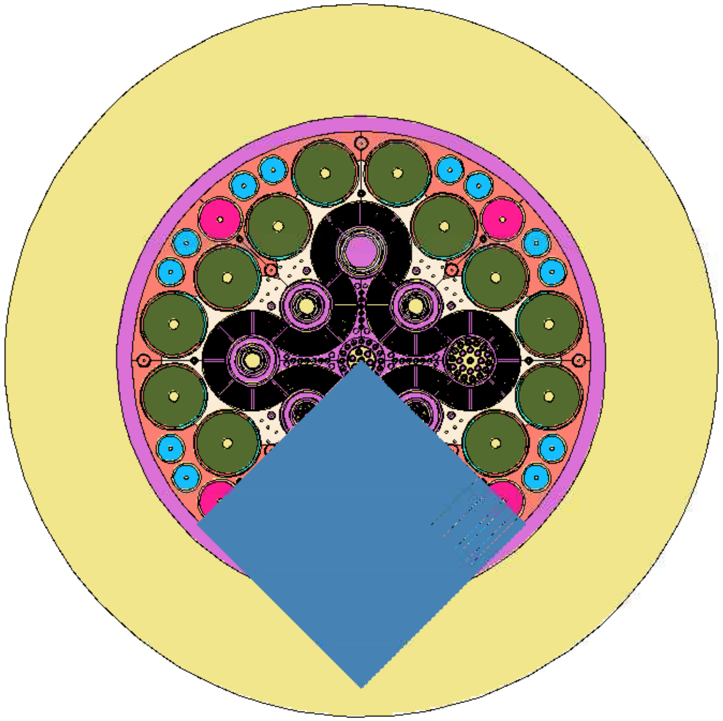


Background: MCCAFE

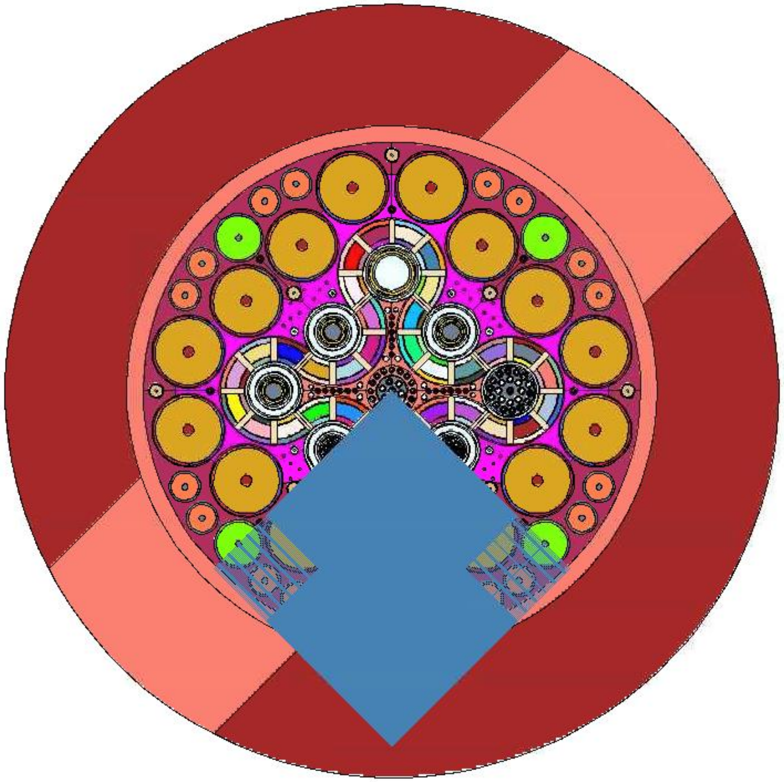
- Monte Carlo Constructor of Advanced test reactor Fuel Elements

Initial comparison of the 3-region model to the 19-plate model

19-Plate Mesh

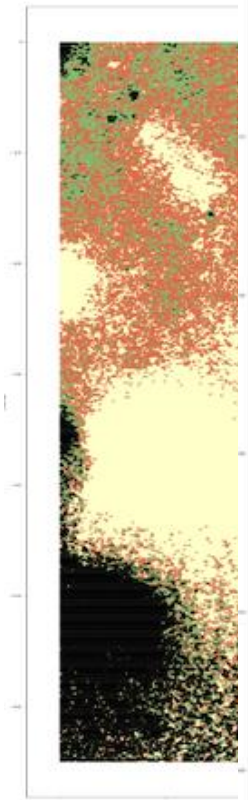


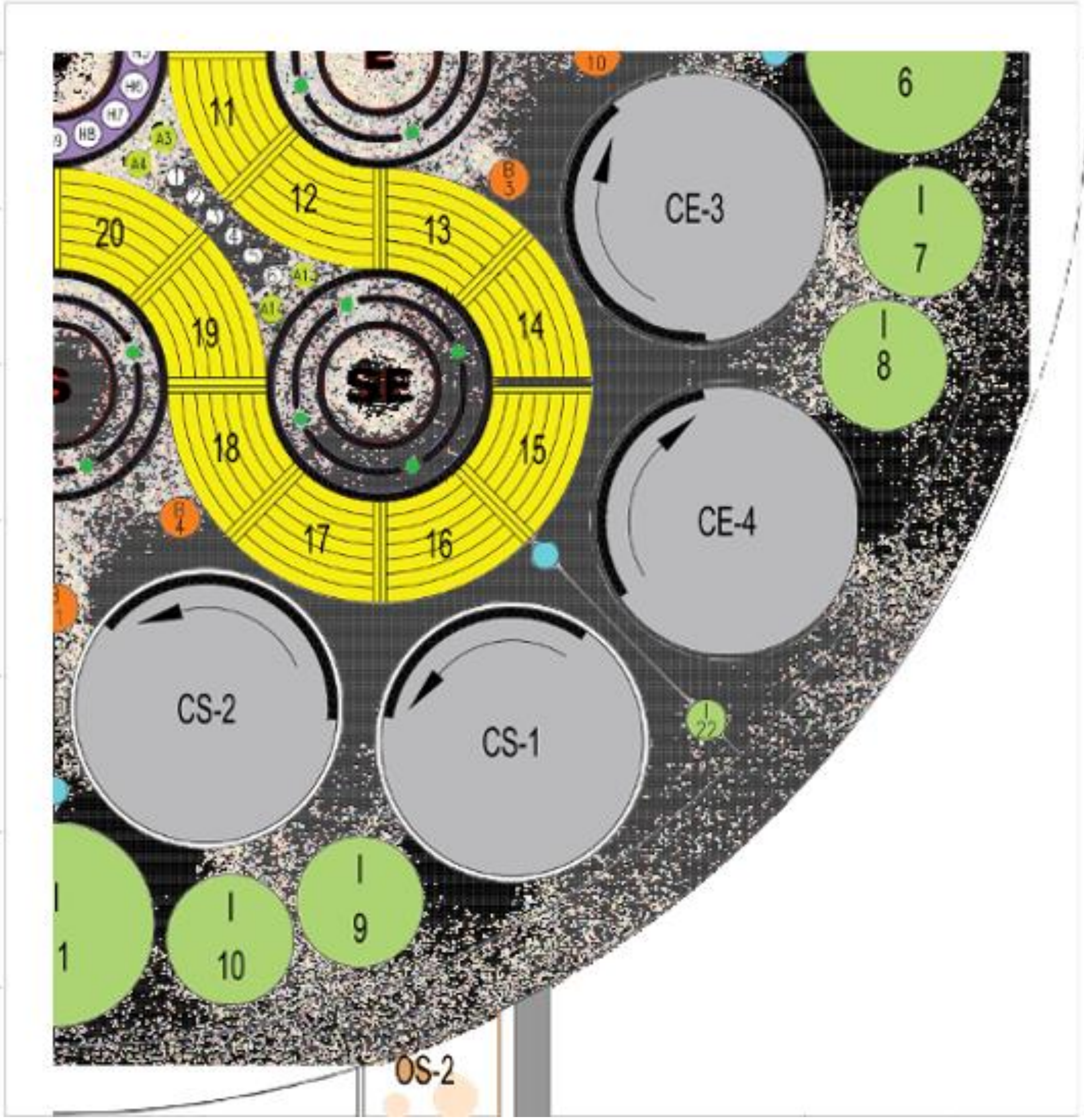
3-Region Mesh

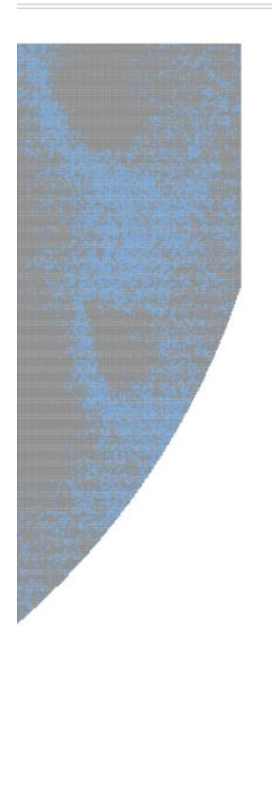


Initial Comparison

19-plate:
0.00015
3-region:
0.00014

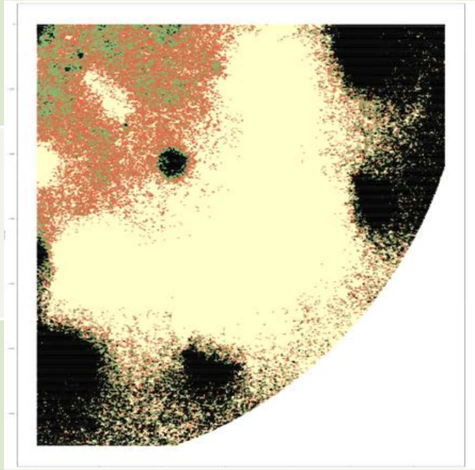






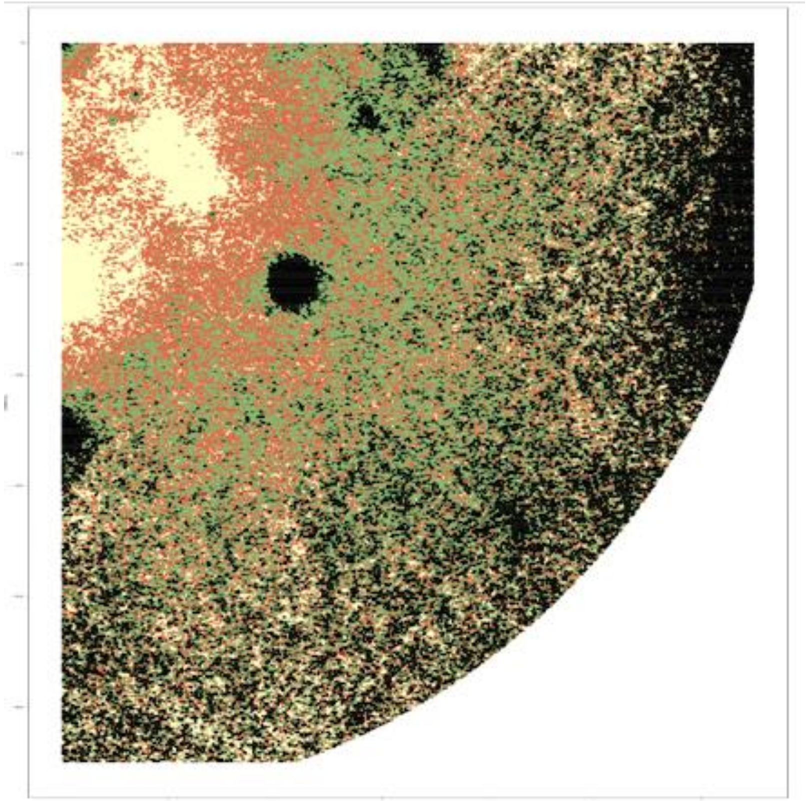
Color Scheme

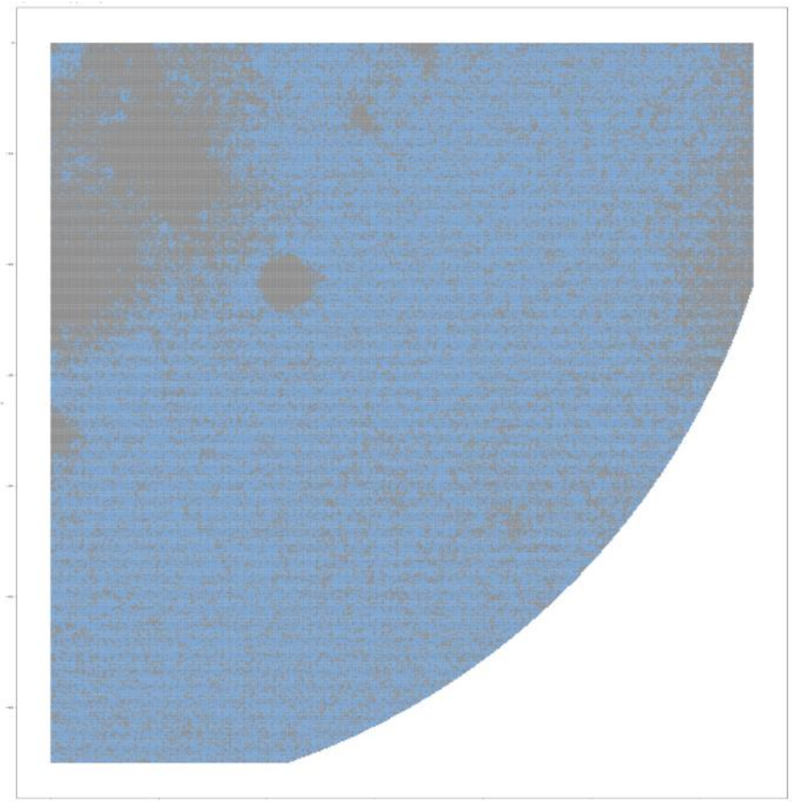
Yellow	Greater than 10% difference where the 3-region model predicts a greater value than the 19-plate model.
Red	Less than 10% difference where the 3-region model predicts a greater value than the 19-plate model.
Green	Less than 10% difference where the 3-region model predicts a smaller value than the 19-plate model.
Black	Greater than 10% difference where the 3-region model predicts a smaller value than the 19-plate model.



Updating the OSCC's

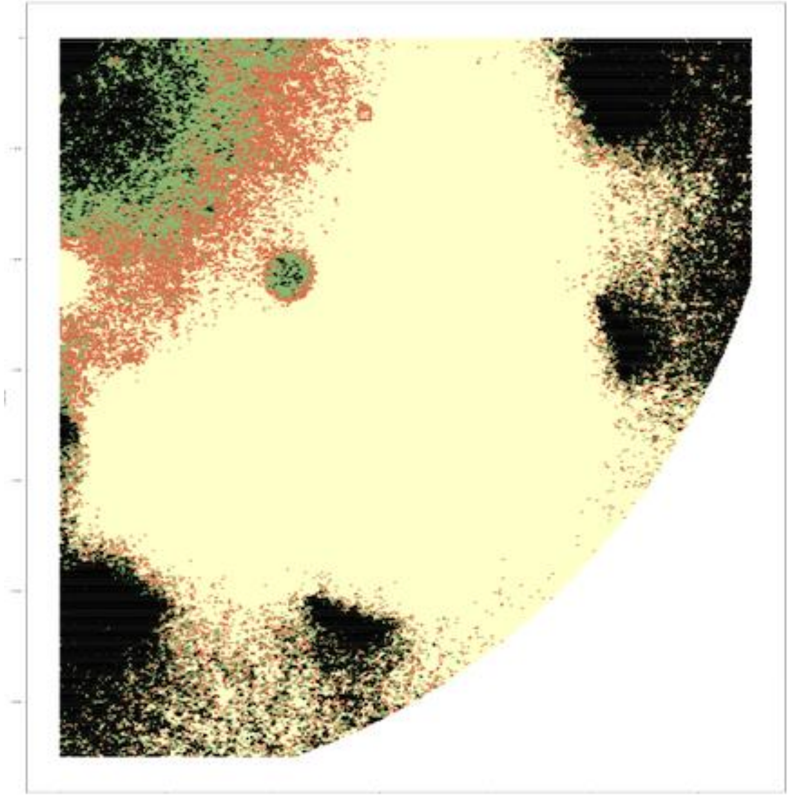
3-Region: 1.02422
± 0.00015

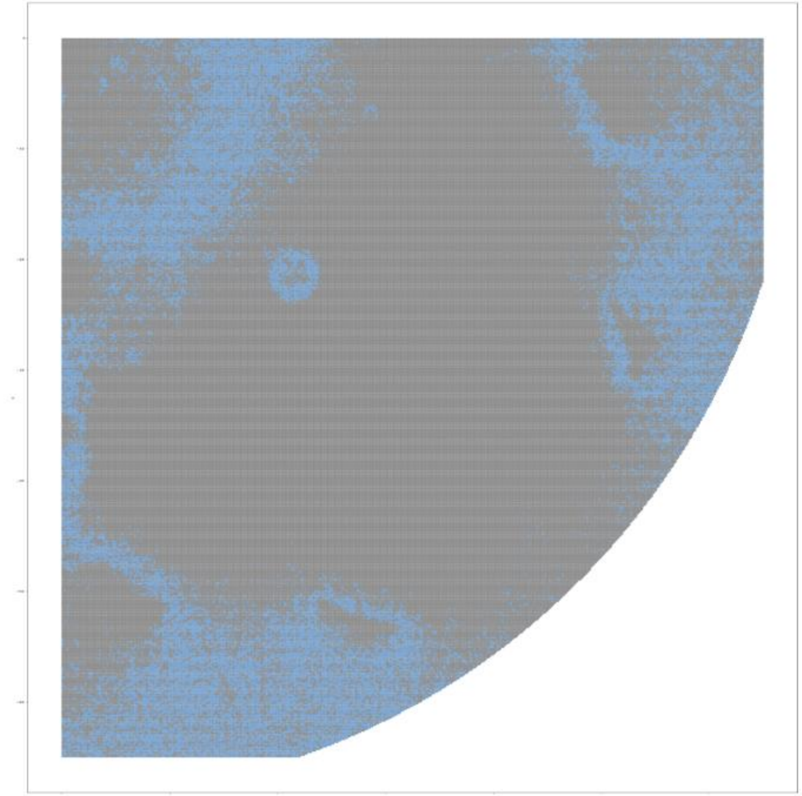




Neck Shims

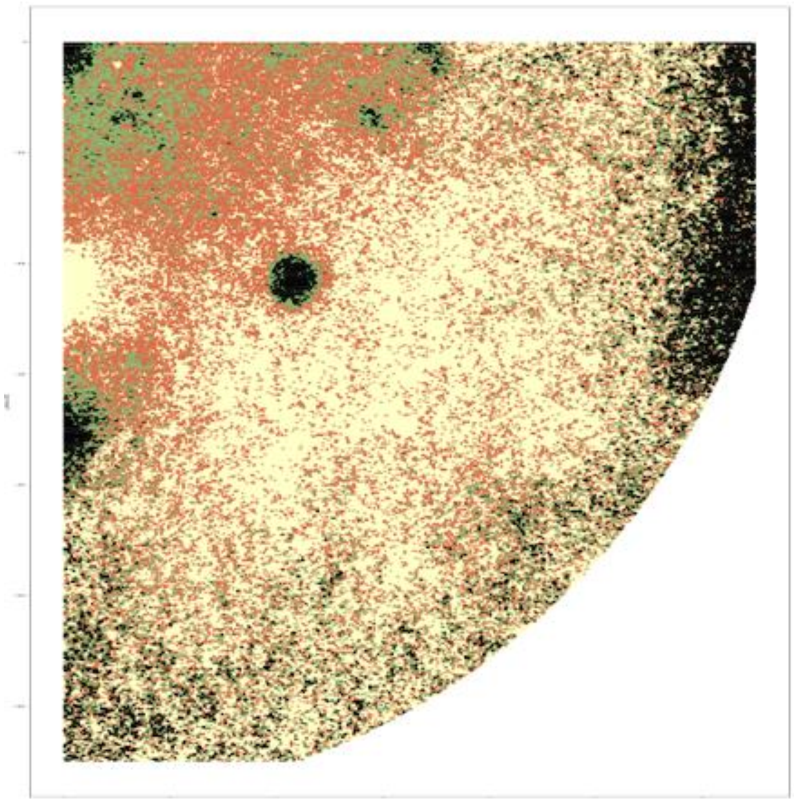
3-Region: 1.01417
± 0.00014

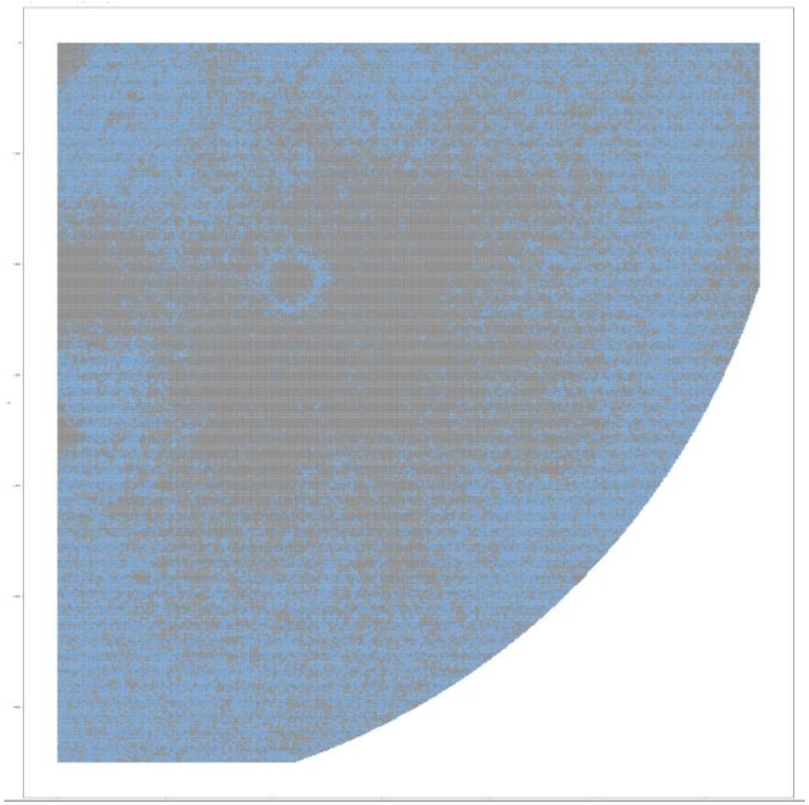




OSCC’s and Neck Shims

3-Region: 0.97130
± 0.00015





19-Plate Model

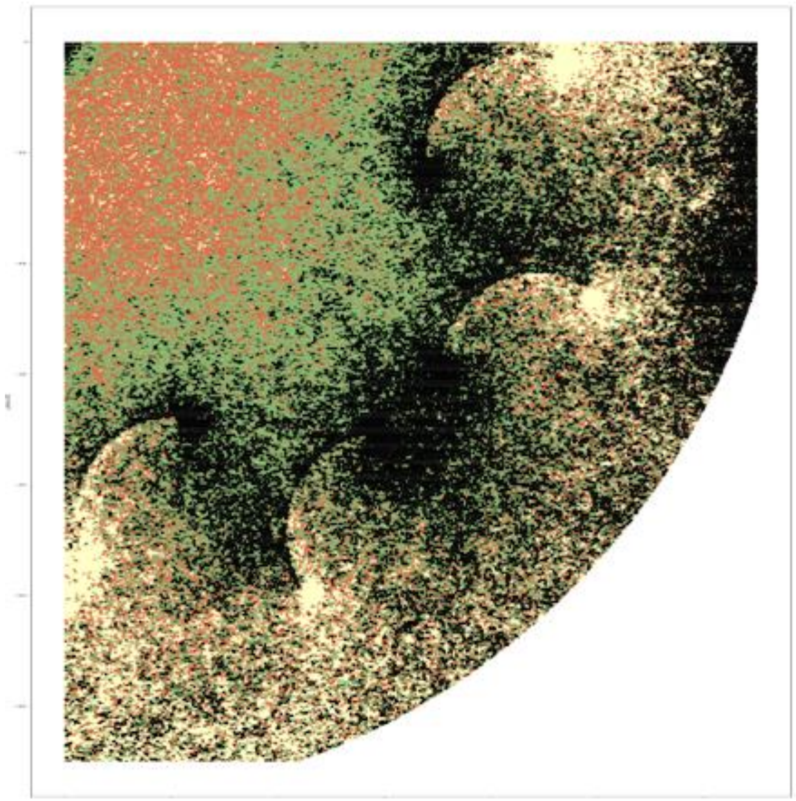
Position	What is Modeled
Center Flux Trap	Cobalt targets
Northeast Flux Trap	Cobalt targets
East Flux Trap	Cobalt targets
Southeast Flux Trap	Aluminum baffle and a hafnium safety rod
South Flux Trap	Cobalt targets
Southwest Flux Trap	Aluminum baffle and a hafnium safety rod
West Flux Trap	Aluminum baffle and a hafnium safety rod
Northwest Flux Trap	Aluminum baffle
North Flux Trap	Aluminum baffle and a hafnium safety rod
All A	Aluminum flow restrictors
Small B	Aluminum flow restrictors
Large B	Beryllium fillers
All I	Beryllium fillers
H	H2,H6, H10, and H14 have flux monitor holders. H3 and H11 have flux wire tubes. The remaining H positions have cobalt targets.

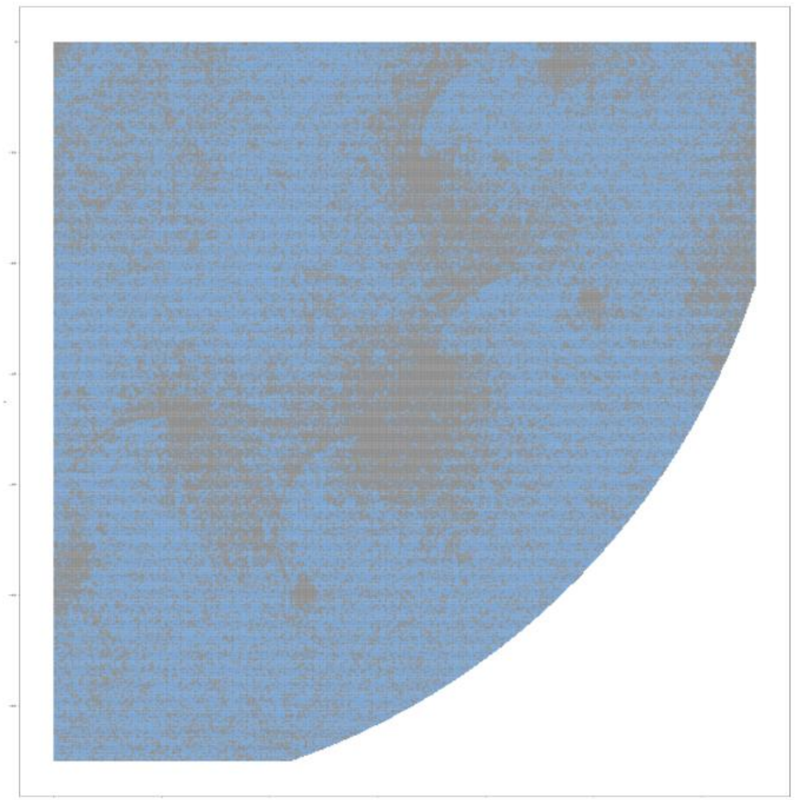
3-Region Model

Position	What is Modeled
Center Flux Trap	Cobalt targets
Northeast Flux Trap	Aluminum baffle
East Flux Trap	Aluminum Filler
Southeast Flux Trap	Aluminum baffle, hafnium safety rod, and an experiment shroud
South Flux Trap	Cobalt targets
Southwest Flux Trap	Aluminum baffle, hafnium safety rod, and an experiment shroud
West Flux Trap	Aluminum baffle, hafnium safety rod, and an experiment shroud
Northwest Flux Trap	Aluminum baffle and an experiment shroud
North Flux Trap	An experiment shroud
All A	A1-A11 cobalt targets, A12 FAST experiment
Small B	cobalt targets
Large B	B9, B11, B12 Aluminum fillers. B12 AGR-1
Large and Medium I	Beryllium fillers
Small I	I21 ATF, I22 FAST, I23 ATF, I24 ATF
H	H1, H4, H5, H7, H8, H9, H12, H13, H15, H16 depleted fixed shim rods. H3, H2, H6, H10, H11, H14 flux wire holder.

Removing Experiments

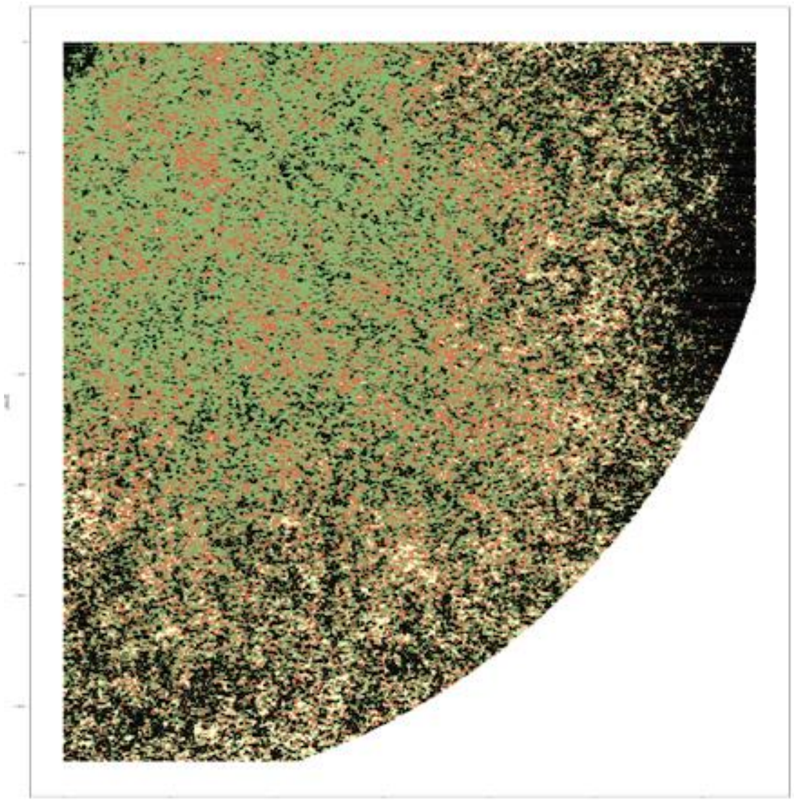
3-Region: 0.97632
± 0.00015

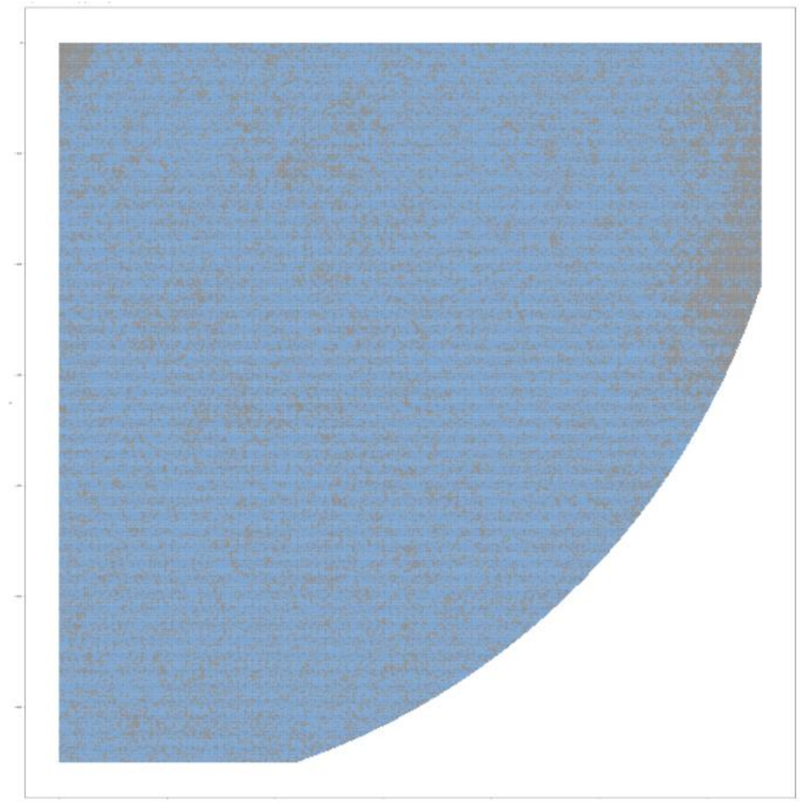




Update Fuel Materials

3-Region: 0.98097
± 0.00015



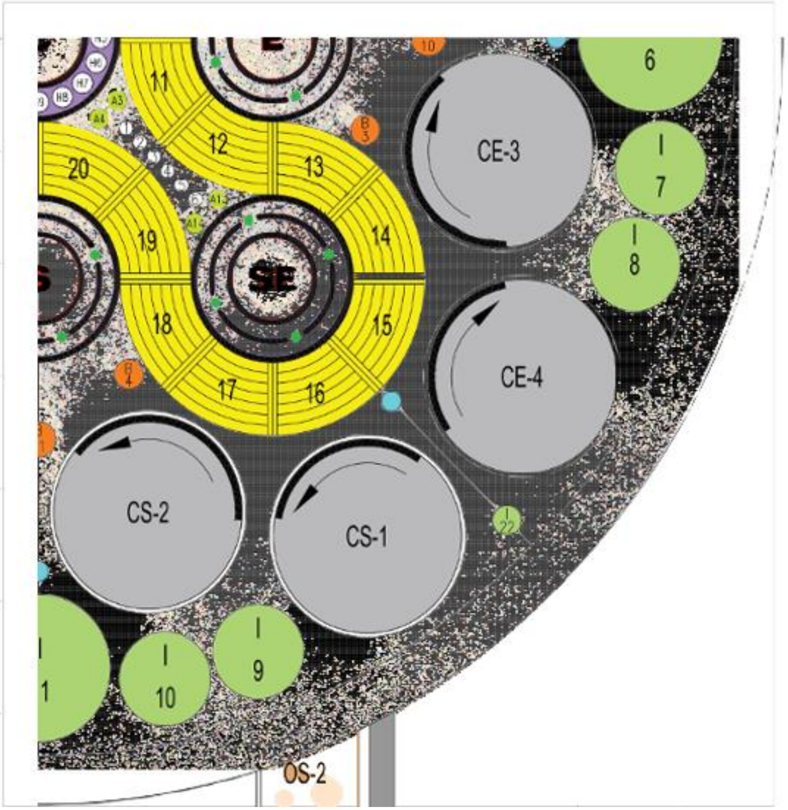


Sensitivity Study

- All A, Small B, H6: Aluminum filler
- Large B, All I: Beryllium
- H5, H7, H8, H9, CFT, EFT, SFT: Cobalt
- SEFT: Aluminum
- Drums: 10, 30, 50, 70, 90, 110, 130, 150 degrees

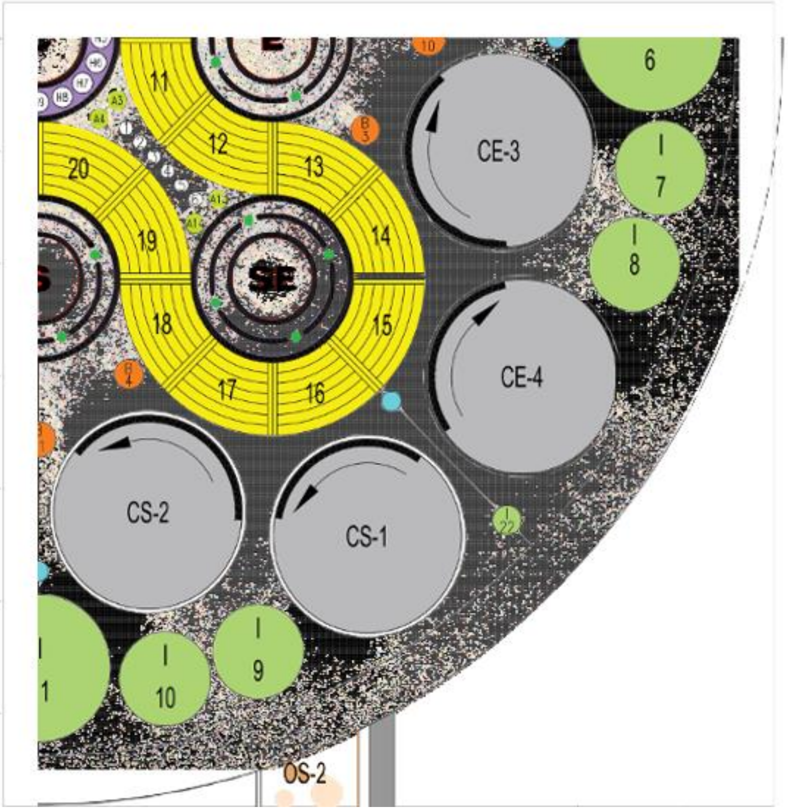
19-Plate model Sensitivity Study Results

Position	Keff Value	Benchmark Error	Model Change in Reactivity ($)	Change in Reactivity Error ($)
Benchmark Model	0.99951	0.00015	NA	NA
A3	0.99517	0.00014	-0.61	0.03
A4	0.99557	0.00014	-0.55	0.03
A10	0.99549	0.00014	-0.56	0.03
A14	0.99622	0.00014	-0.46	0.03
B3	0.99651	0.00014	-0.42	0.03
B4	0.99624	0.00014	-0.46	0.03
B10	0.99901	0.00014	-0.07	0.03
B11	0.99864	0.00014	-0.12	0.03
H5	0.99865	0.00014	-0.12	0.03
H6	0.99634	0.00014	-0.44	0.03
H7	0.99887	0.00014	-0.09	0.03
H8	0.99883	0.00014	-0.09	0.03
H9	0.99879	0.00014	-0.1	0.03
I6	0.99916	0.00014	-0.05	0.03
I7	0.99937	0.00014	-0.02	0.03
I8	0.99897	0.00014	-0.08	0.03
I9	0.99903	0.00014	-0.07	0.03
I10	0.99911	0.00014	-0.06	0.03
I11	0.99893	0.00015	-0.08	0.03
I22	0.99897	0.00014	-0.08	0.03
Shim1	1.00158	0.00014	0.29	0.03
Shim2	1.00151	0.00014	0.28	0.03
Shim3	1.00147	0.00015	0.27	0.03
Shim4	0.99782	0.00014	-0.24	0.03
Shim5	1.0016	0.00015	0.29	0.03
Shim6	1.00177	0.00015	0.31	0.03
OSCC 10 Degrees	0.9923	0.00014	-1.01	0.03
OSCC 30 Degrees	0.99418	0.00015	-0.74	0.03
OSCC 50 Degrees	0.99847	0.00015	-0.14	0.03
OSCC 70 Degrees	1.00509	0.00015	0.77	0.03
OSCC 90 Degrees	1.01376	0.00014	1.95	0.03
OSCC 110 Degrees	1.0224	0.00014	3.11	0.03
OSCC 130 Degrees	1.02838	0.00014	3.9	0.03
OSCC 150 Degrees	1.03137	0.00014	4.29	0.03
Center Flux Trap	0.99879	0.00014	-0.1	0.03
East Flux Trap	0.99751	0.00014	-0.28	0.03
Southeast Flux Trap	0.97766	0.00015	-3.11	0.03
South Flux Trap	0.99739	0.00014	-0.3	0.03



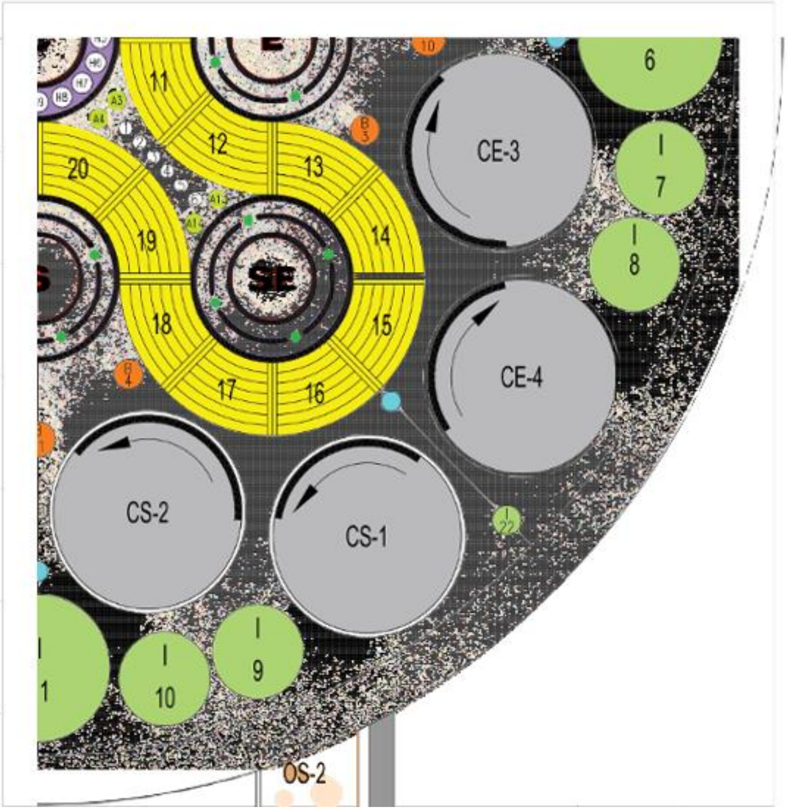
3-Region Sensitivity Study with CFT Geometry Error

Position	Keff Value	3 Region Model Error	Change in Reactivity ($)	Change in Reactivity Error ($)
3 Region Model	0.98097	0.00015	NA	NA
A3	0.97781	0.00015	-0.46	0.03
A4	0.97762	0.00014	-0.49	0.03
A10	0.97745	0.00015	-0.51	0.03
A14	0.97869	0.00014	-0.33	0.03
B3	0.97803	0.00015	-0.43	0.03
B4	0.97823	0.00014	-0.4	0.03
B10	0.97698	0.00014	-0.58	0.03
B11	0.98049	0.00014	-0.07	0.03
H5	0.98024	0.00015	-0.11	0.03
H6	0.97843	0.00014	-0.37	0.03
H7	0.98096	0.00014	0	0.03
H8	0.98069	0.00015	-0.04	0.03
H9	0.98063	0.00015	-0.05	0.03
I6	0.98131	0.00014	0.05	0.03
I7	0.98143	0.00015	0.07	0.03
I8	0.98085	0.00015	-0.02	0.03
I9	0.98125	0.00014	0.04	0.03
I10	0.98104	0.00014	0.01	0.03
I11	0.98115	0.00015	0.03	0.03
I22	0.98125	0.00015	0.04	0.03
Shim1	0.98329	0.00015	0.33	0.03
Shim2	0.98306	0.00015	0.3	0.03
Shim3	0.98331	0.00015	0.34	0.03
Shim4	0.98011	0.00015	-0.12	0.03
Shim5	0.98315	0.00014	0.31	0.03
Shim6	0.98317	0.00014	0.32	0.03
OSCC 10 Degrees	0.97472	0.00016	-0.91	0.03
OSCC 30 Degrees	0.97682	0.00015	-0.6	0.03
OSCC 50 Degrees	0.98029	0.00014	-0.1	0.03
OSCC 70 Degrees	0.98661	0.00014	0.81	0.03
OSCC 90 Degrees	0.99456	0.00014	1.93	0.03
OSCC 110 Degrees	1.00232	0.00015	3.02	0.03
OSCC 130 Degrees	1.00815	0.00015	3.82	0.03
OSCC 150 Degrees	1.01087	0.00014	4.19	0.03
Center Flux Trap	0.98077	0.00015	-0.03	0.03
East Flux Trap	0.97971	0.00015	-0.18	0.03
Southeast Flux Trap	0.9611	0.00014	-2.93	0.03
South Flux Trap	0.97956	0.00014	-0.2	0.03



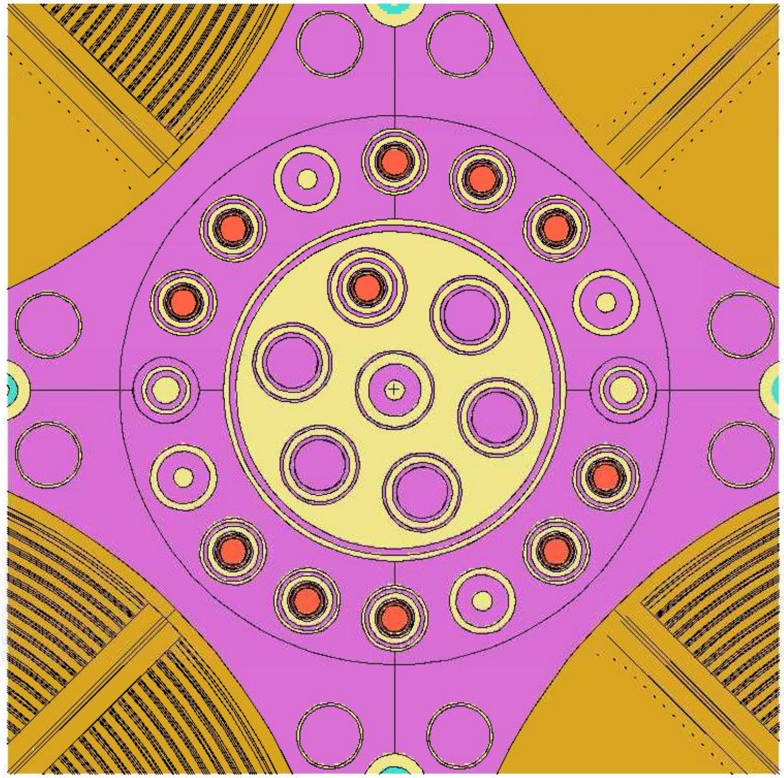
Difference in Reactivity

Position	Reactivity Change Difference (Benchmark - 3 region)
A3	-0.15
A4	-0.06
A10	-0.05
A14	-0.13
B3	0.01
B4	-0.06
B10	0.51
B11	-0.05
H5	-0.01
H6	-0.07
H7	-0.09
H8	-0.05
H9	-0.05
I6	-0.1
I7	-0.09
I8	-0.06
I9	-0.11
I10	-0.07
I11	-0.11
I22	-0.12
Shim1	-0.05
Shim2	-0.02
Shim3	-0.06
Shim4	-0.11
Shim5	-0.02
Shim6	0
OSCC 10 Degrees	-0.1
OSCC 30 Degrees	-0.14
OSCC 50 Degrees	-0.05
OSCC 70 Degrees	-0.04
OSCC 90 Degrees	-2.63
OSCC 110 Degrees	0.1
OSCC 130 Degrees	0.08
OSCC 150 Degrees	0.1
Center Flux Trap	-0.07
East Flux Trap	-0.1
Southeast Flux Trap	-0.18
South Flux Trap	-0.09

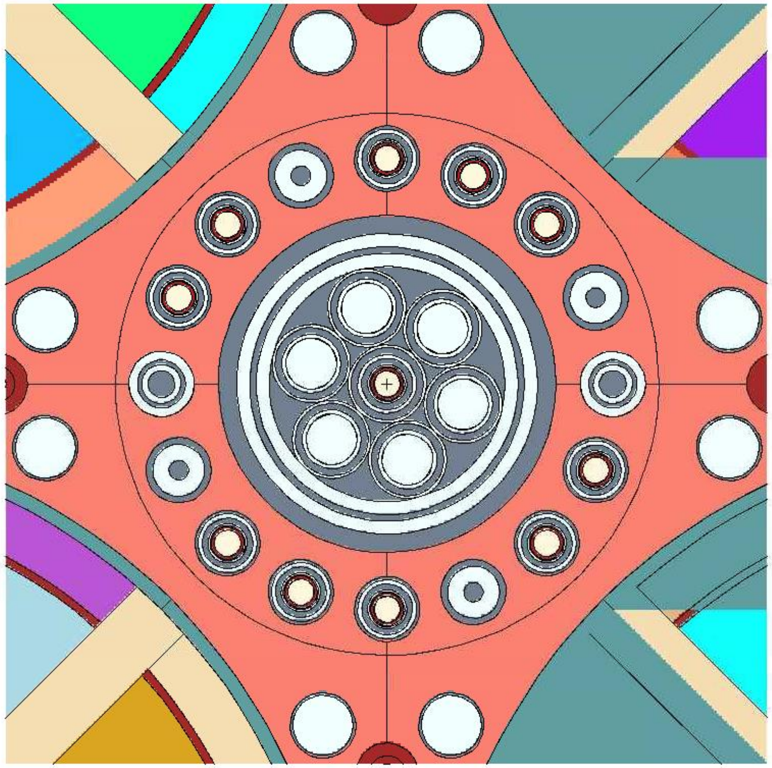


Center Flux Trap Geometry Error

19-Plate CFT

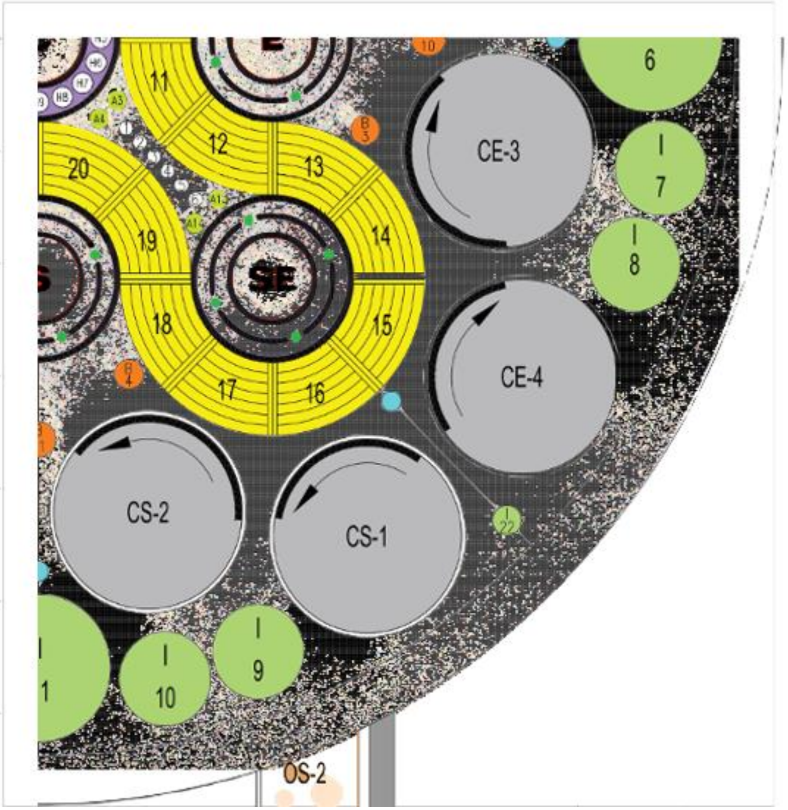


3-Region CFT with error

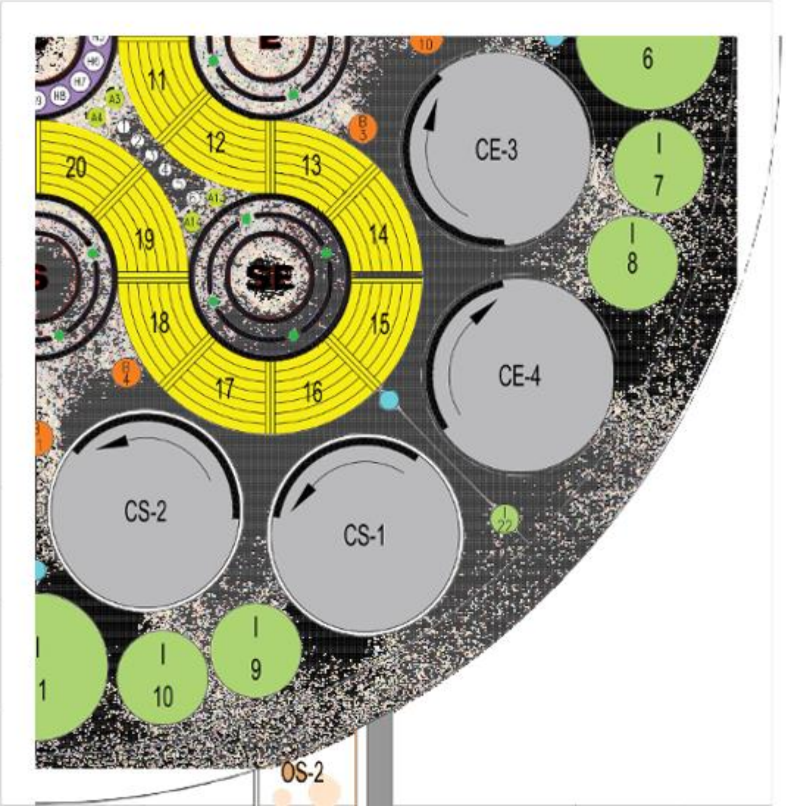


3-Region Sensitivity Study with Correct CFT Geometry

		3 Region Model		
Position	Keff Value	Error	Change in Reactivity ($)	Change in Reactivity Error ($)
3 Region Model	0.97819	0.00015	NA	NA
A3	0.97453	0.00015	-0.53	0.03
A4	0.97481	0.00015	-0.49	0.03
A10	0.97462	0.00014	-0.52	0.03
A14	0.9753	0.00015	-0.42	0.03
B3	0.97529	0.00015	-0.42	0.03
B4	0.97547	0.00014	-0.4	0.03
B10	0.97756	0.00015	-0.09	0.03
B11	0.97746	0.00015	-0.11	0.03
H5	0.97791	0.00015	-0.04	0.03
H6	0.97506	0.00015	-0.46	0.03
H7	0.97774	0.00015	-0.07	0.03
H8	0.9771	0.00015	-0.16	0.03
H9	0.97744	0.00015	-0.11	0.03
I6	0.97797	0.00015	-0.03	0.03
I7	0.97833	0.00015	0.02	0.03
I8	0.97806	0.00015	-0.02	0.03
I9	0.97775	0.00016	-0.06	0.03
I10	0.97791	0.00015	-0.04	0.03
I11	0.97833	0.00015	0.02	0.03
I22	0.97813	0.00014	-0.01	0.03
Shim1	0.98	0.00014	0.26	0.03
Shim2	0.98004	0.00014	0.27	0.03
Shim3	0.98033	0.00015	0.31	0.03
Shim4	0.97682	0.00015	-0.2	0.03
Shim5	0.98051	0.00015	0.34	0.03
Shim6	0.98033	0.00015	0.31	0.03
OSCC 10 Degrees	0.97177	0.00015	-0.94	0.03
OSCC 30 Degrees	0.97361	0.00014	-0.67	0.03
OSCC 50 Degrees	0.97729	0.00014	-0.13	0.03
OSCC 70 Degrees	0.98385	0.00015	0.82	0.03
OSCC 90 Degrees	0.99184	0.00014	1.95	0.03
OSCC 110 Degrees	0.99985	0.00015	3.08	0.03
OSCC 130 Degrees	1.00581	0.00015	3.9	0.03
OSCC 150 Degrees	1.00849	0.00015	4.27	0.03
Center Flux Trap	0.97753	0.00014	-0.1	0.03
East Flux Trap	0.97679	0.00015	-0.2	0.03
Southeast Flux Trap	0.95786	0.00014	-3.01	0.03
South Flux Trap	0.97659	0.00015	-0.23	0.03

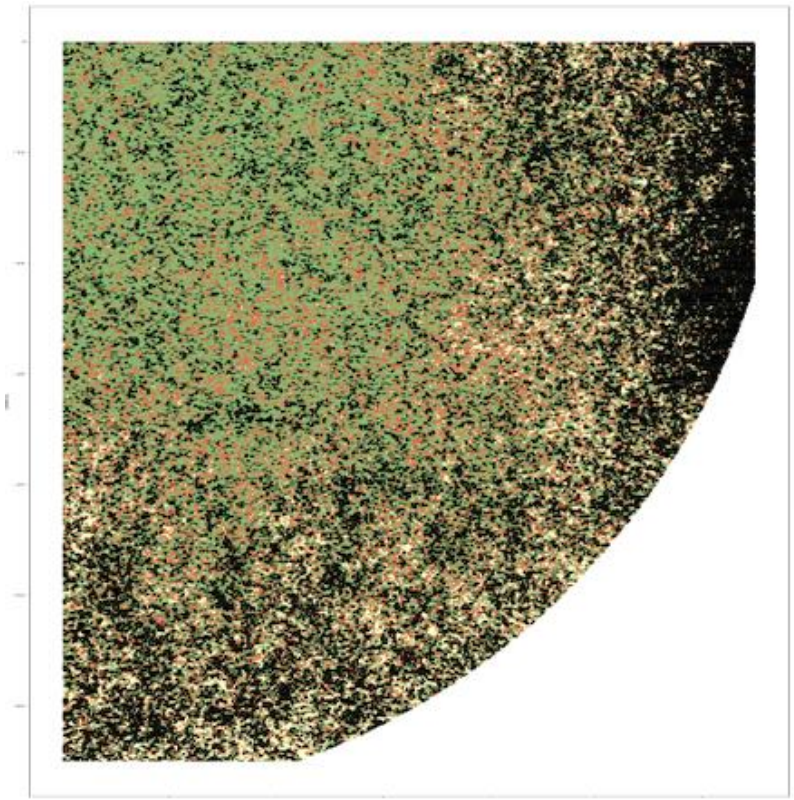


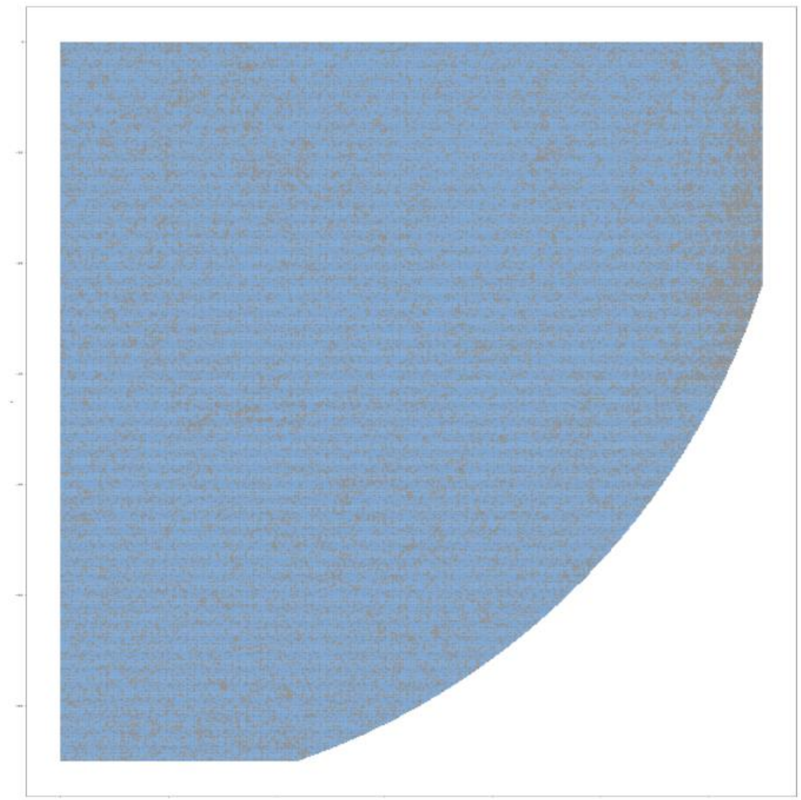
Position	Reactivity Change Difference (Benchmark - 3 region) $
A3	-0.07
A4	-0.06
A10	-0.04
A14	-0.04
B3	0
B4	-0.06
B10	0.02
B11	-0.02
H5	-0.08
H6	0.01
H7	-0.02
H8	0.06
H9	0.01
I6	-0.02
I7	-0.04
I8	-0.06
I9	0
I10	-0.01
I11	-0.1
I22	-0.07
Shim1	0.02
Shim2	0.01
Shim3	-0.04
Shim4	-0.04
Shim5	-0.05
Shim6	0
OSCC 10 Degrees	-0.07
OSCC 30 Degrees	-0.08
OSCC 50 Degrees	-0.01
OSCC 70 Degrees	-0.05
OSCC 90 Degrees	0
OSCC 110 Degrees	0.04
OSCC 130 Degrees	0
OSCC 150 Degrees	0.03
Center Flux Trap	0
East Flux Trap	-0.08
Southeast Flux Trap	-0.09
South Flux Trap	-0.06



Correct Center Flux Trap Geometry

3-Region: 0.97819
± 0.00015

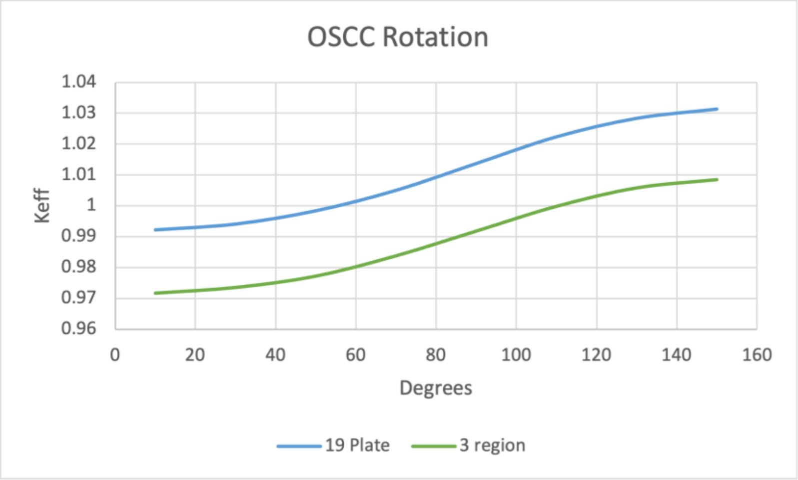


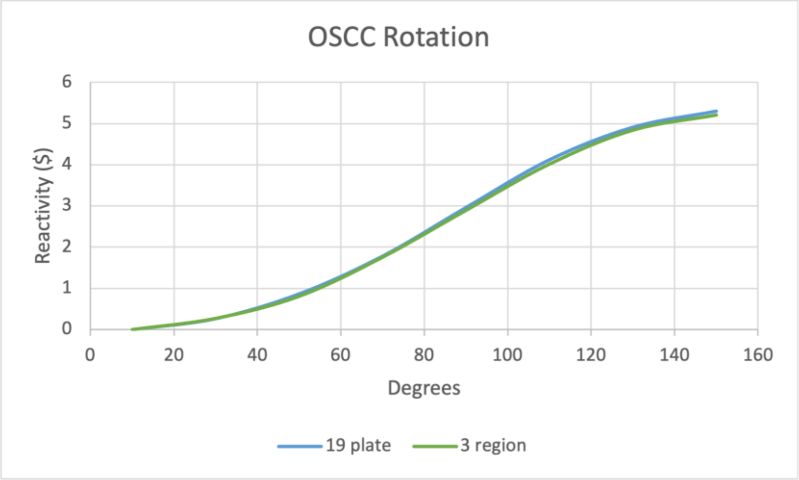


Summary of k-effective Changes

Description of changes	K-effective	Standard Deviation
19-Plate Model	0.99951	0.00015
Unchanged 3-region model	1.05755	0.00014
Changing OSCC positions in the 3-region model	1.02422	0.00015
Changing Neck shim positions in the 3-region model	1.01417	0.00014
Changing both OSCC and neck shim position in the 3-region model	0.97130	0.00015
Removing experiments from the 3-region model	0.97632	0.00015
Modeling fresh fuel in the 3-region model	0.98097	0.00015
Correcting center flux trap geometry in the 3-region model	0.97819	0.00015

Results: Reactivity Curves





Results: Tallies

$$Energy_{lobe} = mass * tally$$

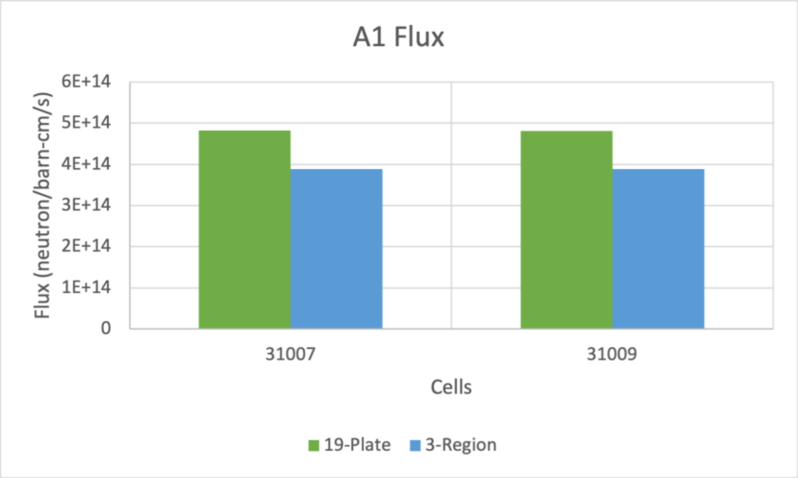
$$Energy_{scaled} = \frac{Energy_{lobe}}{\sum_{1}^{5} Energy_{lobe}}$$

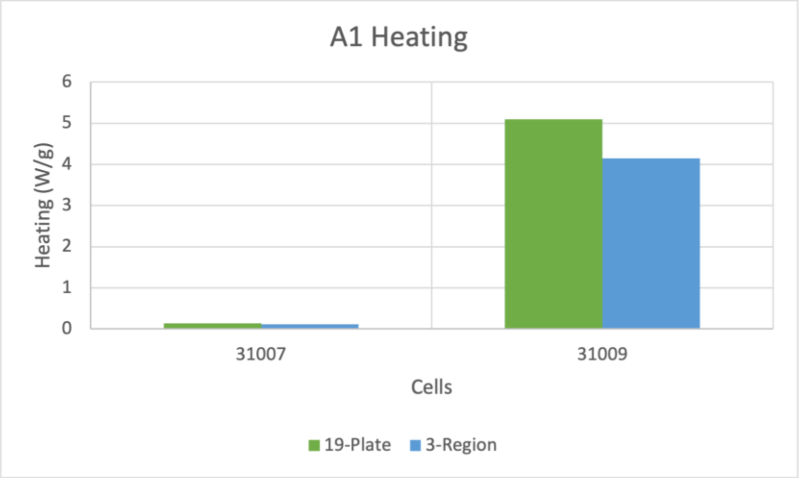
$$Power_{scaled} = \frac{Power_{lobe}}{Energy_{scaled}}$$

Results: Tallies

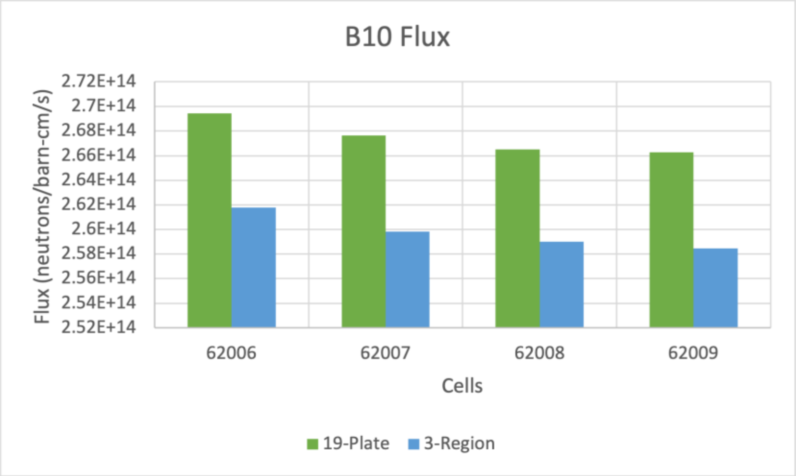
Lobe	19-plate Model Power (MW)	3-region Model Power (MW)
Northwest	109	108
Northeast	115	115
Center	90.1	90.5
Southeast	117	112
Southwest	111	117

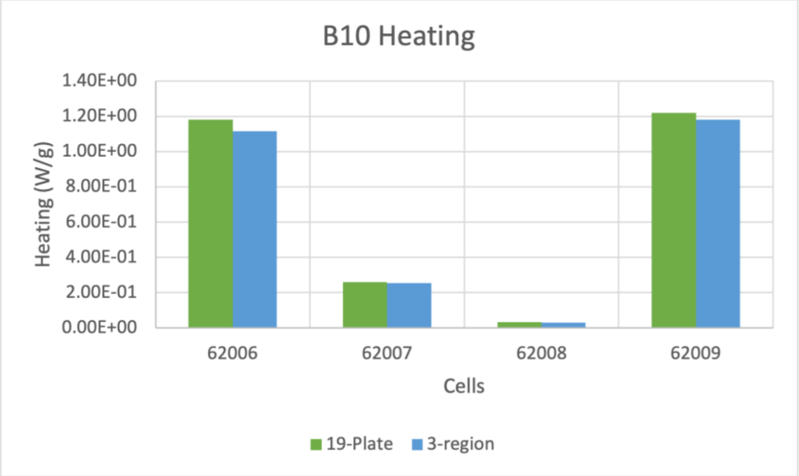
Results: Sample Tallies





Results: Sample Tallies



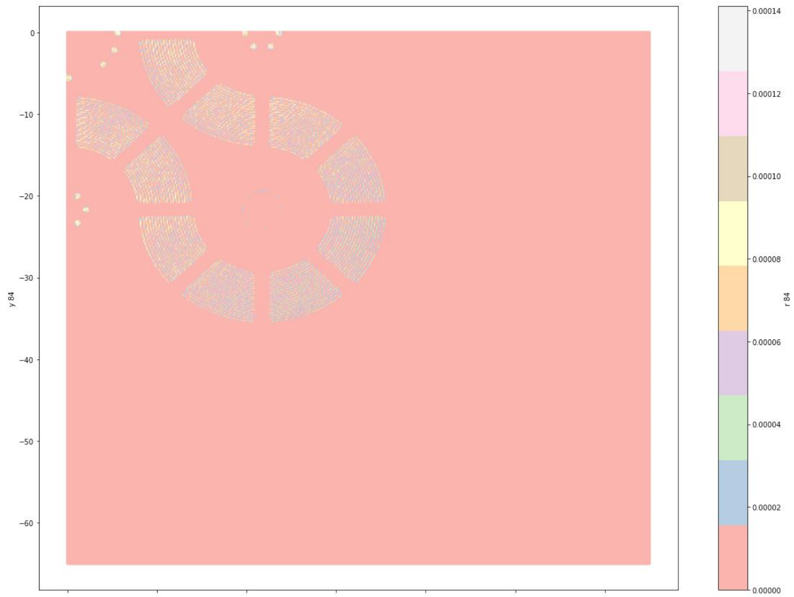


Results: Percent Error Samples

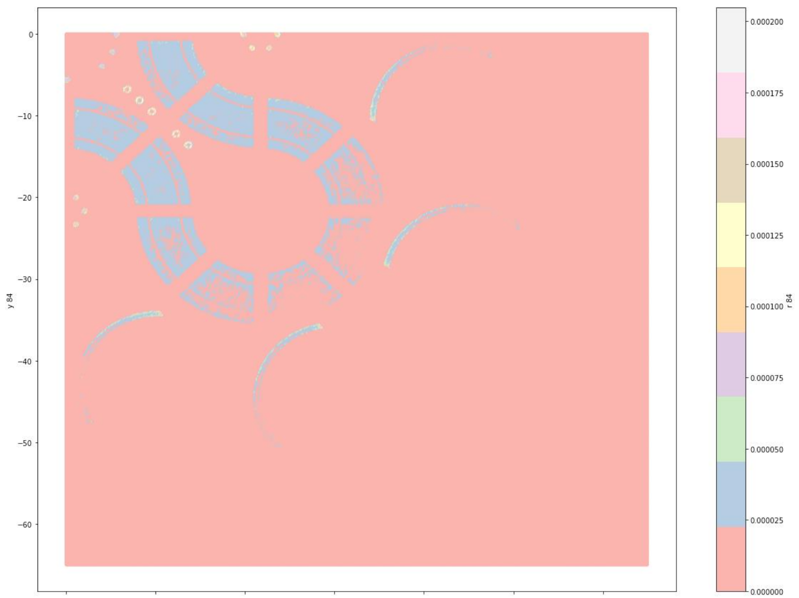
Position	Cell	Flux error	Heat error
A1	31007	19.48	18.33
A1	31009	19.42	18.70
B10	62006	2.84	5.56
B10	62007	2.92	2.76
B10	62008	2.81	2.32
B10	62009	2.94	3.22

Results: Energy Deposition Mesh

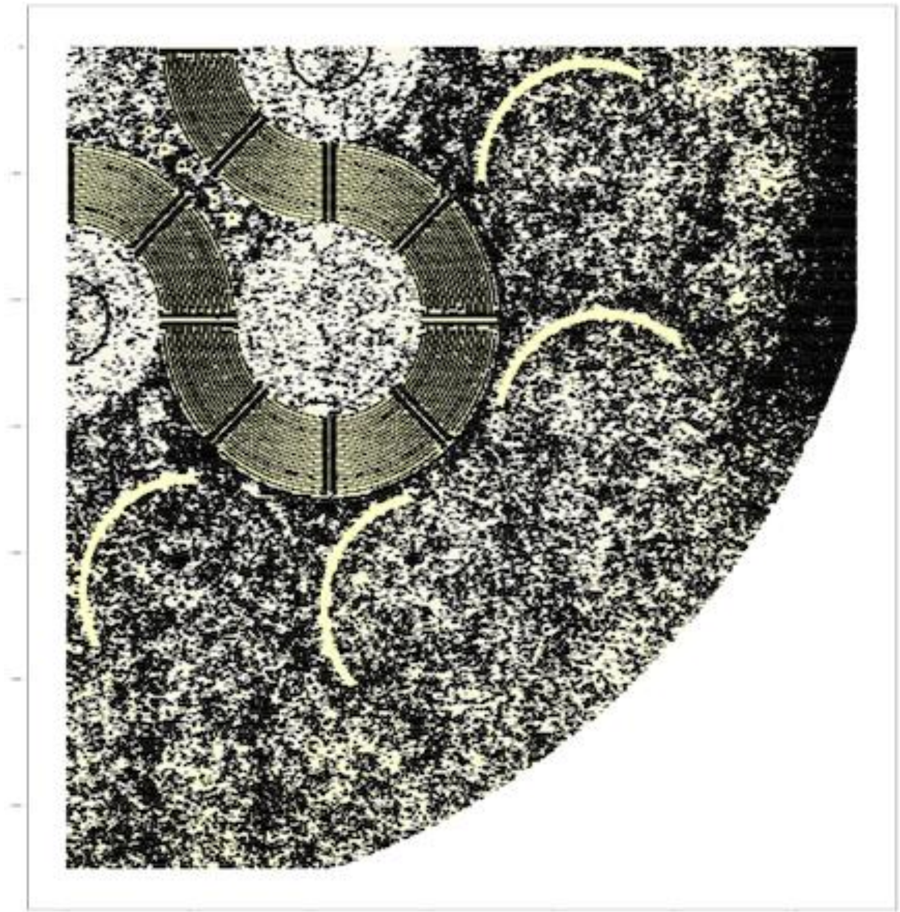
19-Plate Model



3-Region Model

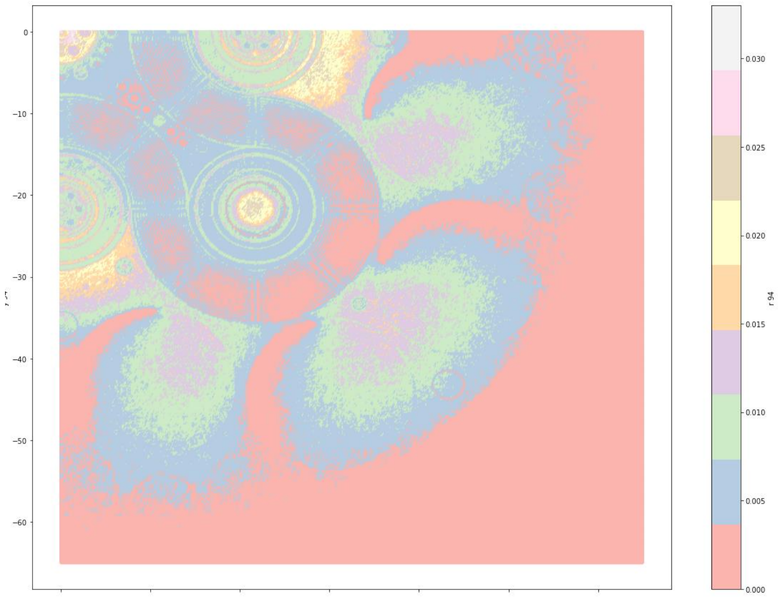


Results: Energy Deposition

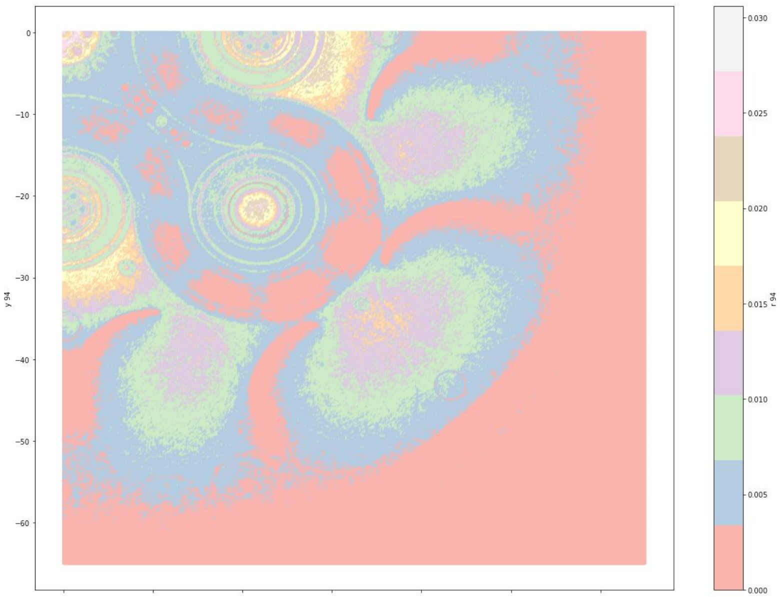


Results: Fission Energy Deposition Mesh

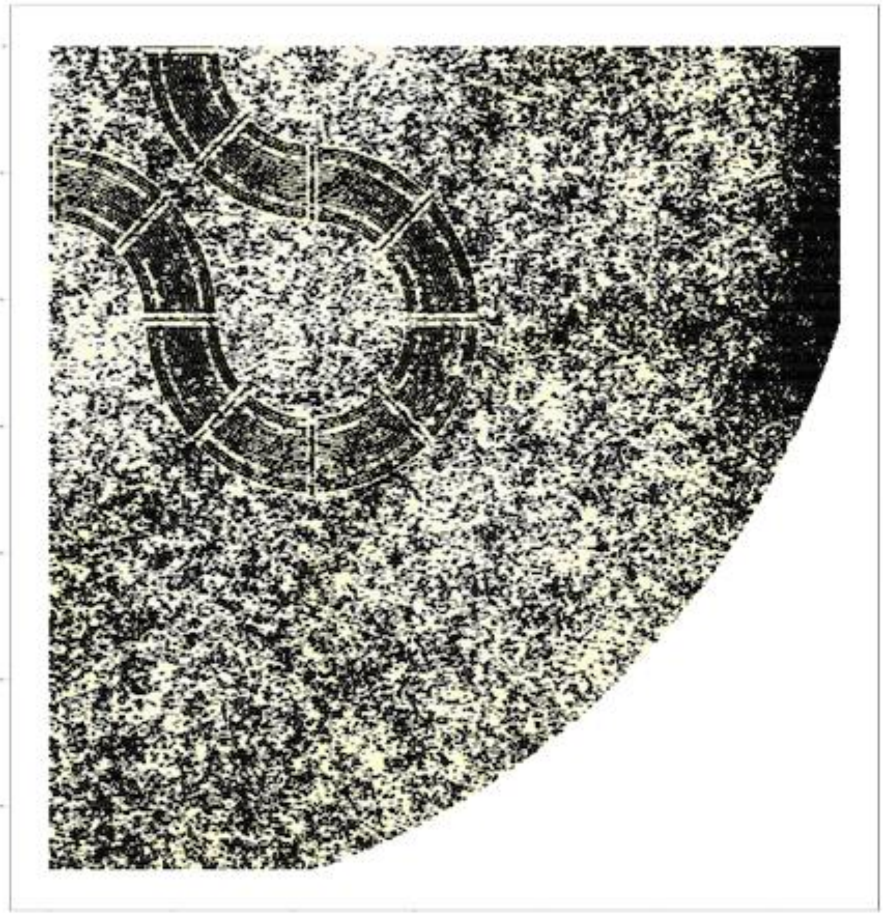
19-Plate Model



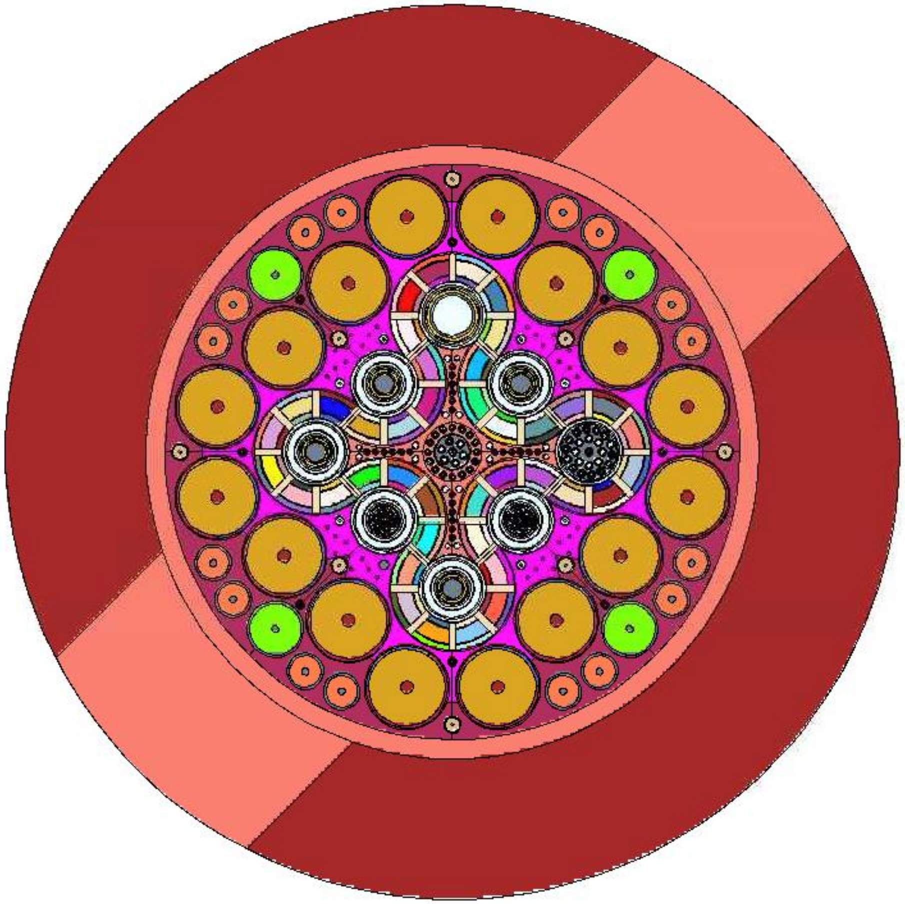
3-Region Model



Results: Fission Energy Deposition



Conclusions: New and Improved 3-Region Model



Conclusions

- https://hpcgitlab.hpc.inl.gov/carbbren/atr_model_tracking
- The 3-region model works for the work it is being used for.
  - Not recommended for k-effective
  - Higher errors inside the fuel ring

Future Work

- Update cross sections used in both the 19-plate model and the 3-region model.
  - Update materials used in the 3-region model
- Investigation into the higher errors inside the fuel ring
- Validation

Idaho National Laboratory

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